SHRP Product Evaluation

Determination of Water-to-Cement Ratio In Fresh Concrete Using Microwave Oven

Interim Report
December 1998

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Abstract

Water-to-cement ratio has been known to be the most valuable information in controlling concrete quality, therefore measuring the water-to-cement ratio of fresh concrete is an important factor that indicates the quality of the concrete being delivered. In the field, strength of properly cured concrete at a given age is assumed to depend primarily only on the water-to-cement ratio and the degree of compaction. The degree of compaction is mostly related to workmanship but the water-to-cement ratio can be adjusted easily by modifying mix proportions as well as the use of admixtures in the concrete mix.

Since early 1970s, highway agencies have recognized the need for tests that measure water-to-cement ratio in fresh concrete. Under the Strategic Highway Research Program (SHRP), the microwave oven drying technique was improved from the original procedure of 60-minute testing to 14-16 minutes, with results accurate enough to qualify as a quality control tool.

This study implement a correction factor from the National Ready-Mixed Concrete Association (NRMCA) and applied it to the New Hampshire Department of Transportation's water-to-cement ratio formula to account for the amount of coarse aggregate in the sample. It was found by the NRMCA that when the proportion of coarse aggregate in the sample is less than its proportion in the batch mix, the water percentage measured from the sample using the microwave oven technique is higher than the actual water percentage from the batch weight. The results show that with proper sampling techniques and applications of the correction factor gives a water-to-cement ratio with a level of accuracy better than 0.01.

Keywords: concrete, water-to-cement ratio, microwave oven

Introduction

For many highway applications, the most important parameter in design and quality control is strength. It has been known that strength is inversely proportional to the water-to-cement ratio. The addition of water in the normal range of water-to-cement ratio for concrete (0.40 to 0.50) affects only the capillary porosity of the concrete. Therefore, the strength of the cement paste depends primarily on the porosity. However, there is no practical and easy method to measure or predict the quantity of these pores. The mix design and quality control of concrete cannot be based on the quantity of these pores.(1) For practical purposes, it explains why measuring the water-to-cement ratio is very useful in determining the quality of concrete being delivered in the field assuming that the concrete will be compacted properly.

In most concrete specifications from highway agencies, both the water-to-cement ratio and the slump are included to assure the concrete strength and the workability of the concrete in-place. In practice, only the slump test is measured to indicate whether additional water was added, either from the aggregates or because of a deliberate addition of water to make the concrete workable and finishable. In many cases, concrete mixes with the same water-to-cement ratio can have totally different slumps.

Many methods have been developed over the years to measure water and cement contents and the water-to-cement ratio of concrete. Unfortunately, none of these methods completely satisfies the needs of highway concrete users. In order to be useable under field conditions, the methods should be simple and rapid.(2)

Since the introduction of the test of fresh concrete using microwave oven in early 1980s, there were many research projects already conducted to refine and to re-evaluate the testing procedures. Encouraging results have been shown with more than 94% mixing water recovery was reported.(3, 4, 5) In addition, the effects of sample size, air entraining agents, fly ash, and other admixtures have been explored from a numerous previous research projects. However, in the early development of the testing procedures, it was indicated that the microwave can actually decompose hydrated cement particles thus increasing the water content.(3) Mixed results also have been obtained during testing.(5)

With the introduction of the SHRP method in determining the water-to-cement ratio in fresh concrete, there was a hope that this method would be implemented in the field immediately. Therefore, replacing other methods that predicting the water-to-cement ratio from hardened concrete. An evaluation project conducted at the Construction Technology Laboratories (CTL) in Skokie, Illinois, implemented various admixtures included silica fume, air entraining agents, high-range water reducer, fly ash, and latex. In addition, different types of aggregates with different aggregate absorption values were included in the evaluation. The results were very encouraging with more than 91% mixed water recovery. (2)

The conclusion from the CTL study indicated that there was no apparent correlation of recoveries with initial water content of the mixes or absorption of the coarse aggregate. On the contrary, some agencies expressed some concerns about the variations in the percentage of water recovered from the concrete mixes tested in the field. The National Ready-Mixed concrete Association (NRMCA) re-evaluated the test procedures and indicated that although the type and absorption value of the coarse aggregate did not affect the percentage water recovery from the concrete mix but the amount of coarse aggregate in the sample did. This amount of coarse aggregate in the concrete sample was indicated as the source of error in determining the percentage of water in concrete mixes using this microwave oven procedure.

Scope of Study and Objectives

This study was initiated as a Strategic Highway Research Program (SHRP) implementation program within the Indiana Department of Transportation (INDOT) to apply these new testing procedures in the field. Since the introduction of the AASHTO TP-23 procedures, the water percentage in the concrete mix can be determined using this microwave oven technique. With a proper mix design and the use of well-controlled modern ready mix plants, the cement content in the mix can be determined from the submitted ticket by the concrete supplier. Therefore, if the water content from the mix can be determined then the water-to-cement ratio can be calculated. However, it was believed that correction factors should be applied to account for the coarse aggregate amount in the concrete mix and the absorption of the coarse aggregate. In addition, the microwave oven procedures should give a value of water-to-cement ratio rather than water percentage. With this emerging test method for fresh concrete and a trend toward performance-based specifications, water-to-cement ratio in fresh concrete becomes necessary.

This project was initiated to evaluate the new SHRP procedure in testing the water-to-cement ratio based on the condition in the field. Since SHRP and New Hampshire Department of Transportation already developed the overall procedures, this study will only evaluate the testing procedures to minimize the variations of the water-to-cement ratio based on:

- Sampling technique: amount of coarse aggregate in the sample
- Amount of sample: the weight of the sample to be tested
- Time: from mixing to placement of concrete
- Workability: effects of admixtures and high slump

The results will verify a correction factor given by the National Ready-Mixed Concrete Association (NRMCA) to account for the amount of coarse aggregate in the sample. It was suspected that when the proportion of coarse aggregate in the sample is less than the amount in the mix design (or trial batch), the water percentage of the mix will be higher than that of the mix design or the trial batch mix. Inconsistency of the amount of sample can influence the measurement of the water-to-cement ratio. This problem relates to the amount of coarse aggregate in the sample. In a case when a sample is taken and the weight is less than the suggested 1,500 grams there is a possibility that the water percentage will be higher than the mix design.

The time from mixing to testing the concrete also will influence the calculated water-to-cement ratio. In cement chemistry, when water is mixed with cement hydration products will form immediately. These hydration products have water molecules attached to them that exist in different stages. The water in the hydration products is divided into evaporable and non-evaporable water. In ordinary concrete the early hydration in 20 to 25 minute period will not produce sufficient amount of hydration products to make the concrete hard as occurred in high early set or high early strength concrete that will take large amount of water to be non-evaporable.[6] However, there should be some amount of water that cannot be evaporated using the heat generated by the microwave oven. Naik and Ramme[5] already indicated that if samples were allowed to stand for 30 minutes prior to testing, the results indicated about 2% to 4% error from known values.

The use of water reducing admixtures is not only to disperse the cement particles to make them more exposed to the water molecules for reaction, but also making the mix more workable (more fluidity) that will make the water more available to infiltrate the fine and coarse aggregates. These can make the calculated water-to-cement ratio lower because more amount of water cannot be evaporated easily from very small pores with the heat from the microwave oven. It was suspected that longer drying time is needed for concrete with high slump.[2]

Except in the case of lower amount of coarse aggregate in the sample, in all the cases described above the calculated percentage of water (weight of water/weight of sample) indicated by AASHTO TP-23 procedures will appear lower than the percentage of water from the trial batch. For the same reasons, the calculated water-to-cement ratio (W/C) developed by SHRP and New Hampshire DOT will also appear higher than the water-to-cement ratio calculated from the trial batch mix. Therefore, if an acceptance procedure is based on the calculated water percentage or the calculated water-to-cement ratio there is a possibility that an agency will reject concrete within the specification limit or accept concrete outside the specification limit.

This evaluation study will try to minimize the variations in the water-to-cement ratio. Therefore, these new testing procedures can be used as a quality control tool with an accuracy of the water-to-cement ratio very close to the highway agency's specification. Guidelines and a correction factor should be introduced to correct the calculated water-to-cement ratio to its design value. The correction factor has to be analyzed also based on the allowable tolerances for strength or performance of concrete. In this case, how many psi (or MPa) in compressive strength can be tolerated in the acceptance procedure.

Materials and Method

Based on the SHRP procedure the main equipment for this test, which is the microwave oven, should have a power setting of 900 watts. In this study, a commercial microwave oven 1,200 watts was used. A pyrex glass tray was used to hold a sample of approximately 1,500 grams of fresh concrete. A digital scale accurate to within 0.01 gram, a grinding pestle, and a spatula were used for weighing and placing the sample. A fiberglass cloth was used to cover the sample. In an earlier attempt, a thicker fiberglass cloth from a different company was used. Because of the difference in thickness, the result from this thicker cloth was not as accurate the thinner one.

The aggregates in the samples came from two different sources. The first group came from a gravel source in Indianapolis area and the second group of crushed limestone samples came from McCordsville, Indiana. The coarse aggregate used in the first group of samples was gravel with absorption capacity of 1.52% and specific gravity of 2.616. The fine aggregate was natural sand with absorption capacity of 1.50% and specific gravity of 2.605. The coarse aggregate for the second group of samples was crushed limestone with absorption capacity of 1.24% and specific gravity of 2.667. The fine aggregate was natural sand with absorption capacity of 1.07% and specific gravity of 2.643.

A neutralized Vinsol resin solution air entraining agent and a Type F high-range water reducing admixture were used in the fifth group of samples. The selection for use of these admixtures is somewhat arbitrary because an agency can select the admixtures from other sources. However, the most important thing is to know the time effect of each of the admixtures.

The mix design of the concrete samples followed the American Concrete Institute (ACI) 211 procedures. The estimated water-to-cement ratio was 0.44 and the slump was 7.5 to 10 centimeters to give approximately 38 MPa of compressive strength at 28 days.

The testing procedure to determine the water percentage in the concrete samples conformed with the AASHTO TP-23 procedures. However, before the testing began the selection of power to be used in the microwave oven had to be determined by a calibration procedure. A calibration procedure from the New Hampshire DOT was used with some modifications to match the procedure in the AASHTO TP-23, the weight of the samples, and the characteristic of the microwave oven. The microwave oven used in this study has a power selector of 100%, 80%, 50%, and 30%. The calibration sequence:(7)

1. Oven dry aggregates to constant weight
2. Weigh aggregates, cement and water to make a sample of approximately 1,500 grams
3. Mix the constituents in a pan then add water and mix until homogenous mixture is obtained (about 1 minutes)
4. Place the fiberglass cloth into the pyrex container
5. Place the mixture into a pyrex container, make sure to use a rubber spatula to ensure all materials are placed in the pyrex container and wrap the sample with the fiberglass cloth
6. Weight the mixture in the pyrex container
7. Place the sample in the pyrex container to the microwave oven and set the microwave oven at 100% power for 5 minutes
8. Remove the sample from the microwave oven and grind the sample with the pestle to expose more surface to be dried
9. Wrap and place the sample into the microwave oven and set the microwave oven at 100% power for 5 minutes
10. Remove the sample and chop the sample with a steel spatula to avoid agglomeration.
11. Weigh the sample

12. Place the sample in the pyrex container to the microwave oven and set the microwave oven at 100% power for 2 minutes
13. Weigh the sample and subtract it from the original weight. This weight should be a little bit less than the weight of the original water (about 1 to 2 grams less)
14. If the weight loss is greater than original weight of water, fines are being burned
15. Reduce power to 80% and repeat steps 1 to 13 until weight loss about 1 to 2 grams less than the original water
16. Record power setting

In this study it was found that running at 100% with that typical brand of microwave oven and the 1,500 grams of concrete samples gave very accurate results. The procedures described in AASHTO TP-23 were followed closely due to the sensitivity of determining the percentage of water evaporated from the sample. Small errors in determining the weight of the evaporated water gave incorrect results. Most of the samples were done testing in about 16 minutes (5 + 5 + 2 + 2 + 2 minutes).

Discussion and Findings

After the development of the concept of using microwave oven in drying the concrete sample, many agencies questioned about the accuracy of the result due to the sample characteristics, such as sample size and proportions of the concrete constituents (especially coarse aggregate) in the sample. In short, the ability of the microwave oven to withdraw water from the small pores in the coarse aggregate.

The concern about the amount of coarse aggregate in the sample comes from the fact that in concrete, water will infiltrate the small pores in the coarse aggregate. In addition, the longer the delay from mixing to testing the sample the larger the amount of water infiltrating these pores. During the heating process water vapor is trapped inside the small pores therefore it takes longer time to completely dry the sample. With the newly developed procedure that requires only 15 minutes to finish the test, the measured water percentage will be less than the water percentage from the mix design or the trial batch mix. Therefore, when a group of samples with a constant mortar (water + cement + sand) content and less coarse aggregate contents is tested, the measured water percentage values will be larger than that of mixes with a higher amount coarse aggregate content.

Table 1 shows the test results of Group 1 mixes with four samples. In this first group of samples, the mortar content was held constant while the amount of the coarse aggregate was reduced from Mix1A to Mix 1D. The theoretical as well as the measured water percentage increases with the decrease of the coarse aggregate content. The theoretical and the measured water percentage were very closely matched. In addition, the weight of water evaporated from the sample was also very close to the original water content. The concern that water infiltrated small pores in the coarse aggregate in the mortar-rich mixes was hard to be removed was incorrect.

For samples in Group 1, the results indicated that the smaller the amount of the coarse aggregate in the mix the higher the water percentage. The increases in water percentages in the mixes are a result of the decreases in total weights of the samples. This is a classical example of proportion and specific gravity from various components in the concrete mix. This result indicated that the amount and absorption capacity of the coarse aggregate in a sample should be taken into account when the water-to-cement ratio was to be determined. In addition, the weight of the sample should be held constant, 1500 grams for a typical microwave oven.

The formula to calculate the water percentage based on AASHTO TP-23 is:

$$WC = 100 \times \frac{(WF - WD)}{(WF - WS)}$$

Where:

WC	= water content percentage
WD	= mass of tray + cloth + dry specimen
WF	= mass of tray + cloth + fresh specimen
WS	= mass of tray + cloth

The correction factor from the NRMCA was introduced to calculate the AASHTO TP-23 water percentage. The correction factor was based on the amount of coarse aggregate in the sample and described as follow:

$$CF = \frac{[1 - (CA_{batch})]}{[1 - (CA_{sample})]}$$

Where:

CA_{batch}	= batch weight of coarse aggregate
CA_{sample}	= weight of coarse aggregate in the sample

The calculated water-to-cement ratio developed by New Hampshire DOT is based on the absorption of the aggregates as described below:

$$\frac{W}{C} = [(N + 1) \times MD] - N \times [\{ACA \times (1 - FA)\} + AFA \times FA]$$

Where:

N	= (total aggregates weight)/(cement weight)
MD	= (wet weight – dry weight)/(dry weight)
FA	= ratio of sand to total aggregate
ACA	= absorption of coarse aggregate (decimal)
AFA	= absorption of fine aggregate (decimal)

When the NRMCA correction factor was applied to mixes in Table 1 the water percentages of Mixes 1B to 1D closely matched the water percentage of Mix 1A, the target mix. However, the disadvantage of this correction factor to the AASHTO TP-23 formula was the lack of information about the amount of the coarse aggregate in the tested sample (dry CA_{sample}). In addition, knowing the water percentage will not give any information about the properties and quality of the concrete being tested. A decrease of 1% of the water percentage does not correlate with either the strength or the performance of the concrete being tested.

The concept from the New Hampshire DOT will give more meaningful perception about the concrete being tested. An increase of 0.01 in water-to-cement ratio will decrease the strength approximately 125 psi (0.9 MPa). However, the results in Table 1 indicated that when the water-to-cement ratios (W/C) of Mixes 1B to 1D were calculated using the New Hampshire DOT formula with the amount of coarse aggregate unknown, the calculated value deviated significantly from the target Mix 1A. This result indicated that the formula from the New Hampshire DOT is very sensitive to the amount of coarse aggregate in the sample.

After numerous trials, it was found that when the correction factor from the NRMCA was applied to the (wet weight – dry weight)/(dry weight) or MD in the New Hampshire DOT formula, this corrected water-to-cement ratio became very close to the water-to-cement ratio of the target mix 1A. Applying this correction factor to the original New Hampshire DOT W/C formula corrected the measured W/C against the deviation of the W/C due to the absorption from the aggregates and the amount of coarse aggregate in the mix.

In Table 1, the term *New Hampshire DOT W/C (CA unknown)* means that the water-to-cement ratio was calculated using the New Hampshire DOT formula with the amount of the coarse aggregate from the control Mix 1A. This is an actual situation that will be encountered in the field, an operator will not know the exact amount of coarse aggregate in the sample. The term *New Hampshire DOT W/C (CA known)* means that the water-to-cement ratios in Mixes 1B to 1D were calculated using the New Hampshire DOT formula with the corresponding amounts of coarse aggregate from each mix. This result tested the consistency of the New Hampshire DOT formula if the amounts of the coarse aggregate in the samples were pre-determined. The term *Corrected New Hampshire DOT W/C* means that the water-to-cement ratios were calculated using the NRMCA correction factor in the New Hampshire DOT formula using the amount of coarse aggregate from each mix. Figure 1 shows the deviations of *NHDOT W/C (CA unknown)* from the *NHDOT W/C (CA known), Corrected NHDOT W/C*, and the *Batch Weight W/C.*

As the study went on, the sources of coarse and fine aggregates were replaced. To review the consistency of the test method for different aggregates, a series of tests was conducted. There was no adjustment needed for the power of the microwave oven and the time to dry the samples.

Table 2 shows the result of aggregates from the second group of samples with varying amount of crushed limestone for each tested sample. In this test, the amount of mortar was held constant while the proportions of the coarse aggregate in the samples were decreased from Mix 3A to Mix 3H. A similar test set-up as in Table 1 except that the sources of aggregates were not identical. Figure 2 shows the deviation of the *NHDOT W/C (CA unknown)* from the *NHDOT W/C (CA known)* while the *Corrected NHDOT W/C* gave accurate results that were almost identical to the *Batch Weight W/C*. The results in Tables 1 and 2 indicated that the NRMCA correction factor was very much applicable to the New Hampshire DOT formula even in the case of inconsistency of sample weight and coarse aggregate amount in the sample.

In the field, most likely due to sampling, the proportion of the coarse aggregate in a sample will be less than that of in the batch weight even when the sample weight is held constant of about 1500 grams. Table 3 shows the mixes 4A to 4H with a constant sample weight, a constant percentage of cement/(cement + fine aggregate), and a constant *Batch Weight W/C* but decreasing coarse aggregate contents. The mixes in Table 3 simulate the likelihood situation in the field.

The mixes in Table 3 shows a situation when a technician takes a sample with less coarse aggregate proportion. The *NHDOT W/C (CA unknown)*, based on the coarse aggregate proportion from the control mix (Mix 4A), will be overestimated. The *Batch Weight W/C* in Mix 4A was 0.44 while the *NHDOT W/C (CA unknown)* indicated 0.51. The difference in the W/C ratios can be translated to approximately 875 psi. (6.03 Mpa.). With this reduction in concrete strength and the difference of W/C of 0.7, a project supervisor absolutely will reject this “right-to-the-specification” and good concrete.

When the NRMCA correction factor introduced to the New Hampshire DOT formula, the *Corrected NHDOT W/C* was very close to that of the *Batch Weight W/C*. Figure 3 shows a large deviation of the *NHDOT W/C (CA unknown)* without a correction factor from the *NHDOT W/C (CA known)* and the *Corrected NHDOT W/C*. The *Corrected NHDOT W/C* values are almost identical to the *Batch Weight W/C*.

There was a concern that the time (from mixing to sampling of concrete) and workability of concrete influences the water-to-cement ratio calculation. With the use of superplasticizer and other admixtures, concrete can have a higher slump or workability. The consequence is water can easily infiltrate the pores in the aggregate and it is difficult to be removed during the microwave drying. In addition, especially in concrete chemistry, a period of time from mixing to sampling of concrete creates very early hydration products with non-evaporable water that cannot be removed in the microwave drying process. It was believed that a rapid evolution of heat in stage 1 on cement hydration due to hydration of compounds in the cement in the first 15 minutes. Many experiments have been conducted to study the early hydration of cement with some difficulties to determine precisely the exact reactions. However, based on some experiments, it was believed that a peak on a Differential Thermal Analysis (DTA) for reaction products, ettringite appeared in the first 15 minutes and a peak of C-S-H gel appeared after 1 hour.(6)

In Type I (ordinary) Portland cement, the C_3A content (the reaction product is ettringite) is only 12 percent by weight while the C_3S (the reaction product is C-S-H gel) is 50 percent. However, there are 32 water molecules attached to the ettringite and only 3 molecules attached to the C-S-H gel. With the existence of evaporable and non-evaporable water in concrete, there should be a certain amount of water loss due to combined water that cannot be evaporated with this microwave oven technique. [6]

Table 4 shows the effect of workability, time delay, and early hydration concrete. A superplasticizer and an air entraining admixture were incorporated into the Mixes 5B to 5D while Mix 5A is the control mix without any admixture and timed for only three minutes (mixing and placing the sample into the microwave oven). Mixes 5B to 5D were mixed for two minutes and stayed in the sample container for 25 minutes with agitation every five minutes. The existence of non-evaporable water was clearly indicated by the weight of water removed from the sample by the microwave oven drying. For those particular mixes, the combined water due to hydration was about two grams, while the deviation of W/C from the control mix 5A was only 0.01, a very small value.

The results in Table 4 imply that samples tested after 25 minutes will give a W/C of about 0.01 lower than that of the Control Mix 5A. It means that there is a possibility that a project supervisor will accept concrete with a higher W/C. However, the 0.01 W/C difference is small in terms of strength of concrete.

There was a concern about the influence of the coarse aggregate absorption. Water trapped on the small pores cannot be easily removed by the microwave drying such in the case of high slump concrete in mixes 5B to 5D. A companion 686.04 gram coarse aggregate sample from mixes 5B to 5D was soaked in water for 30 minutes and was dried in the microwave oven for 7 minutes (5 + 2 minutes). The process removed 100% of the water in the pores of the coarse aggregate. Therefore, the results of the tests in Table 4 are mostly affected by the early hydration of the cement particles. Clearly the effect of workability (higher slump) and time delay have no effect on the amount of removable water from the sample with this microwave oven drying technique.

Conclusions

The results of the study clearly indicate that the water-to-cement ratio in a concrete sample can be measured accurately, quickly, and easily using this SHRP microwave oven drying procedure. With a correction factor from the NRMCA applied into the New Hampshire DOT formula, the accuracy of the water-to-cement ratio becomes better than 0.007 when comparing the *Corrected NHDOT W/C* from the *Batch Weight W/C*. With that small of a value, the difference in concrete strength is only about 87.5 psi (0.602 MPa).

The *Corrected NHDOT W/C* will give an assurance to the project supervisor to accept concrete in the field that meets the highway agency specification while for the supplier there will be no rejection of what supposed to be good concrete. The only remaining concerns are the effect of early hydration of concrete that causes 0.01 deviation to the W/C and the amount of coarse aggregate in the concrete sample to be used in the NRMCA correction factor.

The W/C deviation of 0.01 from the *Batch Weight W/C* by early hydration of cement certainly cannot be applied to every concrete mix. That value will only valid to the particular cement used in this study. However, an agency can develop its own value based on this microwave oven testing easily in less than an hour. In addition, the 0.01 value has a small effect to the concrete strength and to the Quality Assurance/Quality Control (QA/QC) program. Most highway agencies' QA/QC program set a value of 0.03 deviation from the maximum W/C to take action. Therefore, in this particular study an agency can take a risk of 0.01 in W/C or about 125 psi (0.86 MPa) in term of concrete strength.

The amount of coarse aggregate in the sample being tested in the microwave oven can be determined by extracting the coarse aggregate from a companion sample when the concrete is still fresh. This study proposes to take a sample of about 3,000 grams and divide it by two to make two single samples of 1,500 grams. One sample will be tested in the microwave oven to determine the W/C and one sample will be wet-sieved in sieve #4 to extract the coarse aggregate from the fresh concrete. The wet coarse aggregate can be dried using the microwave oven for seven minutes (5 + 2 minute procedure). Once the amount of the coarse aggregate in the sample is determined, the NRMCA correction factor can be calculated and applied.

In three samples that were tested using the wet sieve to extract the coarse aggregate, the procedure can retrieve about 99.37% of the coarse aggregate from the batch weight. The samples were the companion samples of mixes 5B to 5D. There were no lumps or hydration products attached on the surface of the coarse aggregate that would cause errors in determining the amount of the coarse aggregate in the sample. For the control mix in this study, the value of 99.37% is translated to a reduction of 0.0013 in the *Corrected NHDOT W/C*.

In many cases, the sources of variability in concrete strength come from cement (240 psi), batching (462 psi), and testing (188 psi). The overall error is not 890 psi (240 + 462 + 188) but 553 psi (3.81 MPa) that many agencies adopt. With good procedures, practices, modern equipment, and supervision the variation in cement and batching is practically minimized.[8] In this microwave oven test with 0.01 W/C accuracy, the testing variability is down to 125 psi (0.86 MPa). Therefore, this test method is considered accurate as a QA/QC tool.

In the QA/QC principle, it is logical to use a 5% defective level (most agencies have a 10% level) as a permissible percentage outside the specification of W/C. When an agency sets a value of 0.03 variation from the maximum 0.44 W/C (6.81% of 0.44), it means that the agency is willing to take a risk 5% (or 10%) in accepting concrete that has W/C of 6.81% higher than 0.44. Since the W/C accuracy of this test is 0.01 (only 2.27% of 0.44), using this microwave oven procedure opens an opportunity to the highway agency to take advantage in achieving low variability (i.e. good control) in the field by setting the defective level down to 5% and a maximum deviation of 0.01 or 0.02 from the maximum permissible W/C.

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Table 1 – Test Results of Gravel with Constant Mortar Amount (Group 1 samples)

	Mix 1A	Mix 1B	Mix 1C	Mix 1D
Batching				
Weight of Coarse Aggregate (grams)	686.10	661.40	636.10	611.12
Weight of Fine Aggregates (grams)	444.70	444.70	444.70	444.77
Weight of Cement (grams)	304.50	304.50	304.50	304.50
Weight of Total Water (grams)	134.00	134.00	134.00	134.00
Weight of Mixing Water (grams)	116.90	117.28	117.66	118.04
Batch Weight W/C	0.3839	0.3851	0.3864	0.3877
Theoretical Weight (grams)	1569.30	1544.60	1519.30	1494.39
Theoretical Water Percentage	8.54	8.68	8.82	8.97
Testing				
Weight of Wet Sample (grams)	1552.90	1538.40	1510.10	1484.81
Weight of Dry Sample (grams)	1419.70	1404.50	1376.60	1350.81
Weight of Water Removed from Sample (grams)	133.20	133.90	133.50	134.00
Water Percentage by Weight (WC)	8.58	8.70	8.84	9.02
Calculation				
Weight of CA/Total Weight	0.44	0.43	0.42	0.41
Percentage of CA from Control Mix 1A	100.00	96.40	92.71	89.07
NRMCA Correction Factor (CF)	1.00	0.98	0.97	0.95
NRCMA Water Percentage	8.58	8.57	8.56	8.59
New Hampshire DOT W/C (CA unknown)	0.386	0.393	0.401	0.411
New Hampshire DOT W/C (CA known)	0.386	0.387	0.388	0.391
Corrected New Hampshire DOT W/C	0.386	0.386	0.386	0.389

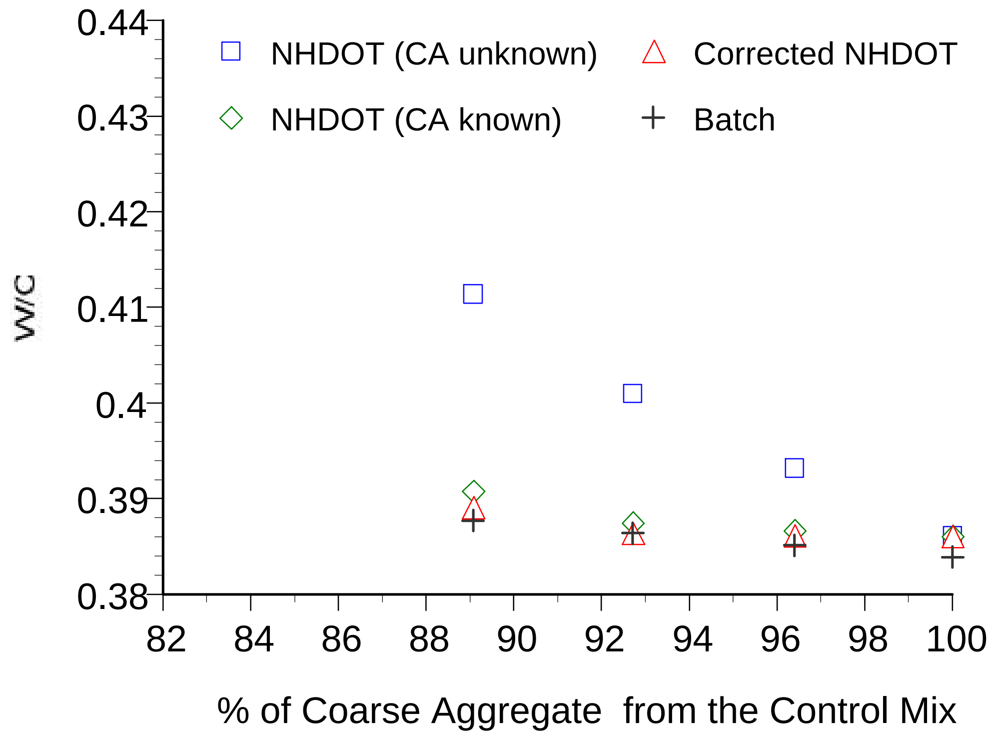

Figure 1 – Test Results of Gravel Coarse Aggregate with Constant Mortar Amount

Table 2 – Test Results of Limestone Coarse Aggregate with Constant Mortar Content

	Mix 3A	Mix 3B	Mix 3C	Mix 3D	Mix 3E	Mix 3F	Mix 3G	Mix 3H
Batching								
Weight of Coarse Aggregate (grams)	686.34	661.78	636.16	624.35	617.80	611.15	600.30	583.34
Weight of Fine Aggregates (grams)	440.54	440.53	440.47	440.53	440.45	440.44	440.42	440.31
Weight of Cement (grams)	304.75	304.57	304.62	304.56	304.54	304.48	304.50	304.46
Weight of Total Water (grams)	147.56	147.51	147.50	147.66	147.58	147.70	147.50	147.55
Weight of Mixing Water (grams)	134.34	134.59	134.90	135.20	135.21	135.41	135.34	135.61
Batch Weight W/C	0.4408	0.4419	0.4428	0.4439	0.4440	0.4447	0.4445	0.4454
Theoretical Weight (grams)	1579.19	1554.39	1528.75	1517.10	1510.37	1503.77	1492.72	1475.66
Theoretical Water Percentage	9.34	9.49	9.65	9.73	9.77	9.82	9.88	10.00
Testing								
Weight of Wet Sample (grams)	1561.97	1543.37	1517.21	1505.14	1494.49	1493.06	1484.44	1466.39
Weight of Dry Sample (grams)	1415.07	1396.02	1370.11	1358.24	1348.09	1345.91	1337.14	1319.59
Weight of Water Removed from Sample (grams)	146.90	147.35	147.10	146.90	146.40	147.15	147.30	146.80
Water Percentage by Weight (WC)	9.40	9.55	9.70	9.76	9.80	9.86	9.92	10.01
Calculation								
Weight of CA/Total Weight	0.43	0.43	0.42	0.41	0.41	0.41	0.40	0.40
Percentage of CA from Control Mix 1A	100.00	96.42	92.69	90.97	90.01	89.04	87.46	84.99
NRMCA Correction Factor (CF)	1.00	0.98	0.97	0.96	0.96	0.95	0.95	0.93
NRCMA Water Percentage	9.40	9.40	9.39	9.38	9.37	9.39	9.38	9.36
New Hampshire DOT W/C (CA unknown)	0.444	0.452	0.461	0.465	0.467	0.470	0.474	0.479
New Hampshire DOT W/C (CA known)	0.444	0.445	0.445	0.445	0.445	0.447	0.447	0.446
Corrected New Hampshire DOT W/C	0.444	0.445	0.445	0.445	0.445	0.446	0.446	0.445

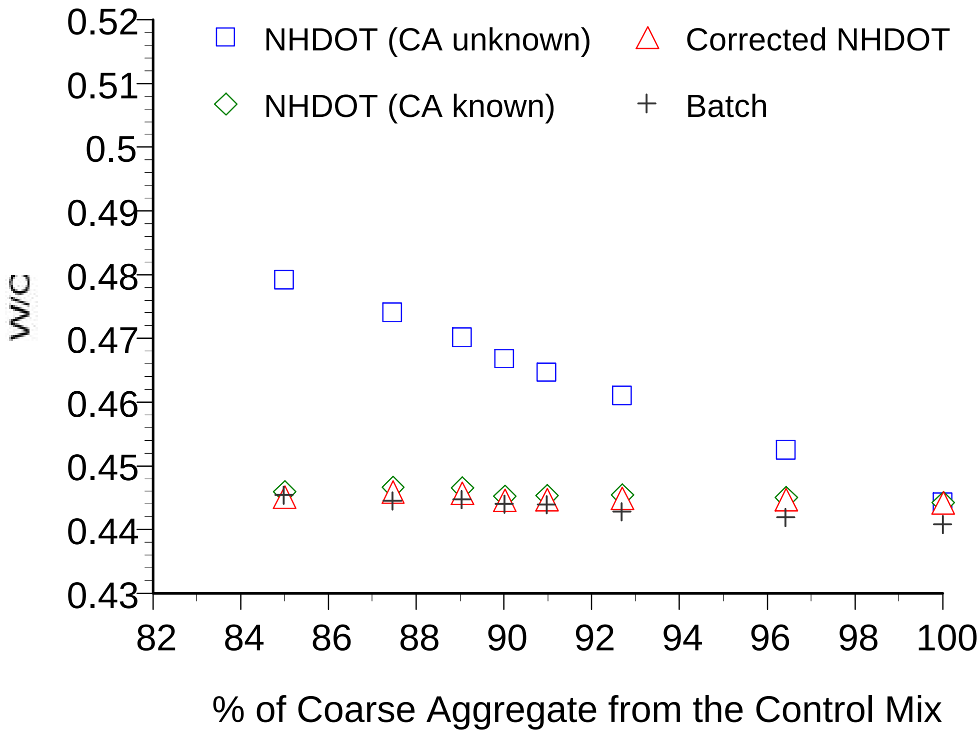

Figure 2 – Test Results of Limestone Coarse Aggregate with Constant Mortar Content

Table 3 – Test Results of Limestone Coarse Aggregate with Constant Sample Weight

	Mix 4A	Mix 4B	Mix 4C	Mix 4D	Mix 4E	Mix 4F	Mix 4G	Mix 4H
Batching								
Weight of Coarse Aggregate (grams)	686.34	658.91	630.08	616.82	609.44	601.89	589.74	570.60
Weight of Fine Aggregates (grams)	440.54	454.38	468.96	475.54	479.29	483.11	489.24	498.89
Weight of Cement (grams)	304.75	314.28	324.42	328.98	331.59	334.22	338.44	345.12
Weight of Total Water (grams)	147.56	151.58	155.84	157.80	158.89	159.99	161.77	164.58
Weight of Mixing Water (grams)	134.34	138.55	143.01	145.06	146.20	147.36	149.22	152.17
Batch Weight W/C	0.4408	0.4408	0.4408	0.4409	0.4409	0.4409	0.4409	0.4409
% Cement/(Cement + Fine aggregate)	40.89	40.89	40.89	40.89	40.89	40.89	40.89	40.89
Theoretical Weight (grams)	1579.19	1579.15	1579.30	1579.14	1579.21	1579.21	1579.19	1579.19
Theoretical Water Percentage (%)	9.34	9.60	9.87	9.99	10.06	10.13	10.24	10.42
Testing								
Weight of Wet Sample (grams)	1561.97	1569.87	1570.47	1569.97	1570.50	1570.34	1571.85	1572.53
Weight of Dry Sample (grams)	1415.07	1418.52	1415.72	1412.22	1411.40	1410.34	1410.40	1406.63
Weight of Water Removed from Sample (grams)	146.90	151.35	154.75	157.75	159.10	160.00	161.45	165.90
Water Percentage by Weight (WC)	9.40	9.64	9.85	10.05	10.13	10.19	10.27	10.55
Calculation								
Weight of CA/Total Weight	0.43	0.42	0.40	0.39	0.39	0.38	0.37	0.36
Percentage of CA from Control Mix 1A	100.00	96.00	91.80	89.87	88.80	87.70	85.93	83.14
NRMCA Correction Factor (CF)	1.00	0.97	0.94	0.93	0.92	0.91	0.90	0.89
NRCMA Water Percentage	9.40	9.35	9.27	9.32	9.33	9.31	9.27	9.34
New Hampshire DOT W/C (CA unknown)	0.444	0.458	0.470	0.481	0.486	0.490	0.494	0.511
New Hampshire DOT W/C (CA known)	0.444	0.443	0.440	0.444	0.445	0.444	0.442	0.447
Corrected New Hampshire DOT W/C	0.444	0.443	0.440	0.443	0.444	0.443	0.442	0.447

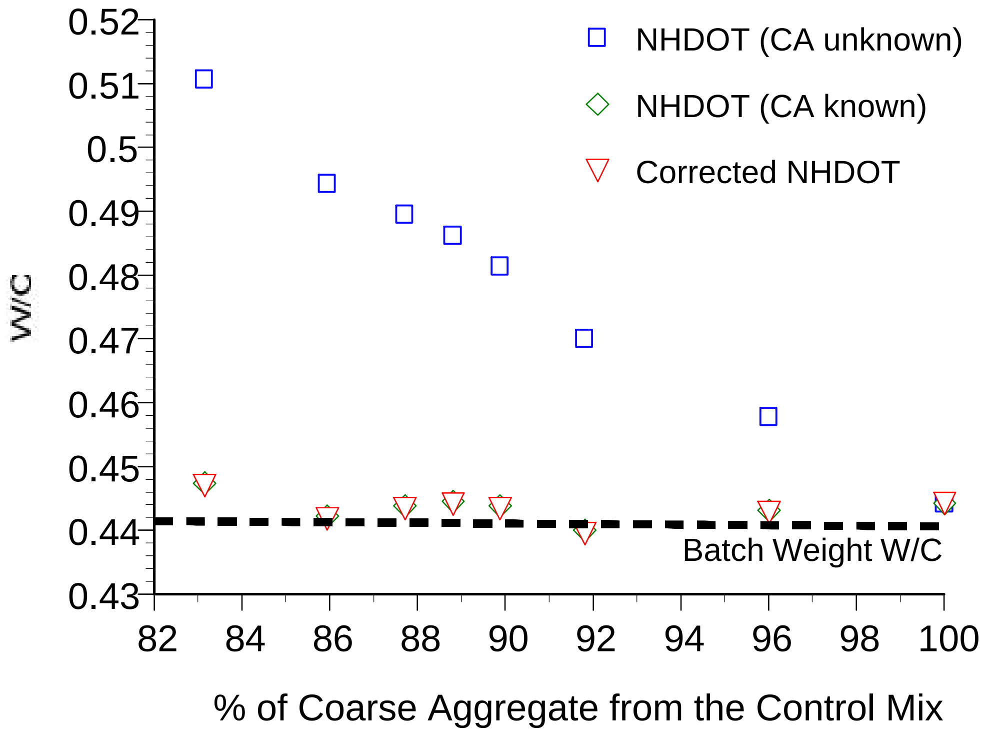

Figure 3 – Test Results of Limestone Coarse Aggregate with Constant Sample Weight

Table 4 – Test Results of Limestone Coarse Aggregate with 25 Minutes Waiting

	Mix 5A	Mix 5B	Mix 5C	Mix 5D
Batching				
Weight of Coarse Aggregate (grams)	686.34	686.34	686.34	686.34
Weight of Fine Aggregates (grams)	440.54	440.54	440.56	440.57
Weight of Cement (grams)	304.75	304.77	304.74	304.75
Weight of Total Water (grams)	147.56	147.56	147.57	147.56
Weight of Mixing Water (grams)	134.34	134.34	134.35	134.34
Batch Weight W/C	0.4408	0.4408	0.4409	0.4408
% Cement/(Cement + Fine aggregate)	40.89	40.89	40.89	40.89
Theoretical Weight (grams)	1579.19	1579.21	1579.21	1579.22
Theoretical Water Percentage (%)	9.34	9.34	9.34	9.34
Testing				
Weight of Wet Sample (grams)	1561.97	1569.69	1569.69	1569.74
Weight of Dry Sample (grams)	1415.07	1424.84	1425.49	1424.54
Weight of Water Removed from Sample (grams)	146.90	144.85	144.20	145.20
Water Percentage by Weight (WC)	9.40	9.23	9.19	9.25
Calculation				
Weight of CA/Total Weight	0.43	0.43	0.43	0.43
Percentage of CA from Control Mix 1A	100.00	100.00	100.00	100.00
NRMCA Correction Factor (CF)	1.00	1.00	1.00	1.00
NRCMA Water Percentage	9.40	9.23	9.19	9.25
New Hampshire DOT W/C (CA unknown)	0.444	0.434	0.432	0.435
New Hampshire DOT W/C (CA known)	0.444	0.434	0.432	0.435
Corrected New Hampshire DOT W/C	0.444	0.434	0.432	0.435