

# **Center for By-Products Utilization**

## **DETERMINATION OF THE WATER-CEMENT RATIO OF CONCRETE BY THE BUOYANCY PRINCIPLE**

By Tarun R. Naik and Bruce W. Ramme

Report No. CBU-1989-12  
January-February 1989

**Department of Civil Engineering and Mechanics College of  
Engineering and Applied Science  
THE UNIVERSITY OF WISCONSIN -- MILWAUKEE**

*This paper presents a procedure developed for the rapid determination of the water-cement ratio of fresh concrete for quality control and quality assurance. The water-cement ratio can be used to evaluate whether the actual concrete composition complies with the job specifications and also to check the uniformity of the concrete within or between batches. The major advantage of using such a method is that concrete can be analyzed immediately when delivered to the job-site. Thus, the concrete could be rejected if it does not meet the project specifications before it is an integral part of the project. The method presented demonstrates potential for rapid jobsite water-cement ratio analysis of fresh concrete.*

Keywords: accelerated tests; buoyancy; fresh concretes; quality control; water-cement ratio.

In today's world of modern construction technology, the ability to determine the composition and potential strength of fresh concrete as soon as possible is becoming more and more important. Since much of today's construction is very rapid, by the time the concrete quality for a project is deemed inferior, it may be too late. If the structure has not collapsed, the inferior concrete may still be buried deep inside the structure where it is very difficult or practically impossible to re-place.

Fortunately, advances have been made in the area of accelerated strength testing,<sup>1</sup> and three methods have been adopted as ASTM standards.<sup>2</sup> All of these methods require at least 24 hr for results.

It would be ideal to analyze concrete before it is placed in the forms. Determining the water-cement ratio of the concrete at a very early stage could determine whether or not the concrete meets the job specifications. Also, checking the uniformity of the concrete (within or between batches) is another possible method for estimating the concrete's strength potential. The water-cement ratio is one of the key factors in determining the quality of a given concrete,<sup>3</sup> and, at the same time, it is the most difficult parameter to measure.

A handful of methods exist for analyzing the water-cement ratio of fresh concrete.<sup>4-9</sup> Unfortunately, none are ideal. An ideal method must be accurate (within a 95 percent confidence level), fast (less than 15 min), simple to perform, inexpensive, independent of ingredient types, and field-worthy.

Popovics<sup>10</sup> and Rhodes<sup>11</sup> have presented a very thorough survey of technical literature concerning the composition analysis of fresh concrete. As Popovics<sup>10</sup> noted, "The importance of determining the composition of fresh concrete is indicated by the fact that numerous principles have been suggested and quite a few test methods have been developed for this purpose."

## THE BUOYANCY METHOD

The basic buoyancy method' allows a rapid determination of the water-cement ratio of fresh concrete by using the buoyancy principle of Archimedes<sup>12</sup>: "A body wholly or partly immersed in a fluid is buoyed up with a force equal to the weight of the fluid displaced by the body." The specific gravity of the cement  $\tilde{\alpha}_{ct}$ , and aggregates  $\tilde{\alpha}_a$ , as well as the ratio of aggregate-to-cement by weight  $B$ , must be known to determine the water-cement ratio. The specific gravity of cement is generally accepted to be 3.15, which varies within a very narrow range when measured; and the specific gravity of aggregates is generally constant for a particular concrete producer and, therefore, only needs to be measured once before the start of a project. Additional tests may be performed also as the project progresses. The weight ratio of the cement and saturated surface dry (SSD) aggregates can be obtained from the concrete mixing plant.

The buoyancy method is based on the Thaulow paper from the 1930s.<sup>4</sup> The underwater weight of an air- free fresh concrete sample  $w_c$ , must equal the sum of the underwater weights of the individual components of the fresh concrete. The underwater weight of water is zero. Therefore, the underwater weight of a normal airfree fresh concrete sample is equal to the sum of the weight of aggregates underwater  $w'_a$  and the weight of cement underwater  $w'_{ct}$

$$w'_c = w'_a + w'_{ct} \quad (1)$$

The underwater weight of the aggregates and the cement can be found by using the specific gravities of the materials, the weight of aggregates in air  $w_a$ , and the weight of cement in air  $w_{ct}$

$$w'_a = \frac{\gamma_a - 1}{\gamma_a} \cdot w_a \quad (2)$$

$$w'_{ct} = \frac{\gamma_{ct} - 1}{\gamma_{ct}} \cdot w_{ct} \quad (3)$$

By combining Eq. (1) through (3) we obtain

$$w'_c = \left( \frac{\gamma_a - 1}{\gamma_a} \cdot w_a \right) + \left( \frac{\gamma_{ct} - 1}{\gamma_{ct}} \cdot w_{ct} \right) \quad (4)$$

The weight of a concrete sample in air  $w_c$  is equal to the sum of the individual components' weight in air where  $w_w$  is the weight of water in air

$$w_c = w_s + w_a + w_w \quad (5)$$

The following equations are developed by using the ratio of aggregate-to-cement by weight in air

$$B = \frac{w_s}{w_a} \quad (6)$$

Dividing Eq. (4) by  $w_{ct}$  and simplifying yields

$$\frac{w'_c}{w_a} = \left( \frac{\gamma_s - 1}{\gamma_s} \cdot \frac{w_s}{w_a} \right) + \left( \frac{\gamma_a - 1}{\gamma_a} \cdot \frac{w_a}{w_a} \right) \quad (7)$$

$$\frac{w'_c}{w_a} = \left( \frac{\gamma_s - 1}{\gamma_s} \cdot B \right) + \left( \frac{\gamma_a - 1}{\gamma_a} \right) \quad (8)$$

$$w_a = \frac{w'_c}{\left( \frac{\gamma_s - 1}{\gamma_s} \cdot B \right) + \left( \frac{\gamma_a - 1}{\gamma_a} \right)} \quad (9)$$

Dividing Eq. (5) by  $w_{ct}$  and simplifying yields

$$\frac{w_c}{w_a} = \frac{w_s}{w_a} + \frac{w_a}{w_a} + \frac{w_w}{w_a} \quad (10)$$

$$\frac{w_c}{w_a} = B + 1 + \frac{w_w}{w_a} \quad (11)$$

$$\frac{w_w}{w_a} = \frac{w_c}{w_a} - (1 + B) \quad (12)$$

Substituting Eq. (9) for  $w_a$  we obtain

$$\frac{w_w}{w_a} = \frac{w_c}{w'_c} \left| \left[ \frac{\gamma_s - 1}{\gamma_s} \cdot B \right] + \left[ \frac{\gamma_a - 1}{\gamma_a} \right] \right| - (1 + B) \quad (13)$$

Eq. (13) can be solved readily, and the water-cement ratio can be found knowing the weight of the concrete test sample in air and underwater, the specific gravity of aggregates and cement, and the aggregate-to-cement ratio used in the concrete mixture.

### Modified buoyancy method

Mathematically, Eq. (13) can be developed further to include a pozzolan. However, the specific gravity of the pozzolan  $\tilde{\gamma}_p$  as well as the ratio of pozzolan-to-cement by weight in air  $C$ , must also be known to determine the water-cement ratio.

Using a similar procedure as described for the basic buoyancy method, the modified equation to account for pozzolan can be developed

$$\frac{w_w}{w_a} = \frac{w_c}{w_c'} \left| \left[ \frac{\gamma_a - 1}{\gamma_a} \cdot B \right] + \left[ \frac{\gamma_a - 1}{\gamma_a} \right] + \left[ \frac{\gamma_p - 1}{\gamma_p} \cdot C \right] \right| - (1 + B + C) \quad (14)$$

Eq. (14) can be solved to yield the water-cement ratio of fresh concrete containing pozzolan. It should be mentioned that Eq. (14) is theoretical, and laboratory research should be performed on concrete containing pozzolan to prove its usefulness. Such work is continuing.

## EFFECT OF BASIC VARIABLES

In planning laboratory work for the buoyancy method, the effect of each variable in Eq. (13) or (14) on the water-cement ratio must be understood.

The weight of the fresh concrete sample in air  $w$ , and that of the fresh concrete sample without air and underwater  $w_c'$  are measured weights and should be obtained to the nearest 10 gm (0.02 lb). This accuracy can be obtained easily in the field with reasonable care. Values for these variables may vary by  $\pm 50$  gm ( $\pm 0.1$  lb), and the water-cement ratio will still result in less than 1.5 percent error (within the 98 percent confidence level). These weights must be obtained for every sample to be tested for the water-cement ratio.

The specific gravity of the aggregates  $\tilde{\gamma}_a$ , the specific gravity of cement  $\tilde{\gamma}_{ct}$ , and the ratio of aggregate-to-cement by weight in air  $B$  are "given" values in Eq. (13). The specific gravity of the aggregates  $\tilde{\gamma}_a$  is the most sensitive variable. The specific gravity of most aggregates averages around 2.65. The value used for  $\tilde{\gamma}_a$  must be accurate to  $\pm 0.01$  to have the water-cement ratio result within a 97 percent confidence level, and to  $\pm 0.02$  to

be within a 94 percent confidence level. The specific gravity of most cement  $\tilde{a}_{ct}$  averages around 3.15. This value can be within  $\pm 0.5$  to have the water-cement ratio within a 97 percent confidence level. The ratio of aggregate to cement  $B$  can vary by  $\pm 0.15$  and the water-cement ratio will still be in the 97 percent confidence level.

If the specific gravity of the aggregates  $\tilde{a}_a$ , the specific gravity of the cement  $\tilde{a}_{ct}$  and the ratio of aggregate to cement  $B$  are all inaccurate to the maximum degrees just specified, the confidence level drops to 92 percent.

The specific gravity of the aggregates  $\tilde{a}_a$ , the specific gravity of the cement  $\tilde{a}_{ct}$ , the specific gravity of the pozzolan  $\tilde{a}_p$ , the ratio of aggregate-to-cement by weight in air  $B$ , and the mix ratio of pozzolan-to-cement by weight in air  $C$  are "given" values in Eq. (14). The effects of  $\tilde{a}_a$ ,  $\tilde{a}_{ct}$  and  $B$  have been discussed for Eq. (13). The specific gravity of pozzolans  $\tilde{a}_p$ , varies from type to type and must be known somewhat accurately for good results by the buoyancy principle. For purposes of comparison and analysis, the value of  $\tilde{a}_p$ , will be assumed to be 2.50. The value used for  $\tilde{a}_p$ , can vary as much as  $\pm 0.05$  to have the water-cement ratio result within the 99 percent confidence level. By varying  $\tilde{a}_p$  by as much as  $\pm 0.25$ , the worst case still yields results within the 93 percent confidence level.

The ratio of pozzolan-to-cement by weight in air  $C$  has a very small effect on the water-cement ratio results. Providing that reasonably accurate data is available on the pozzolan used, theoretically accurate values should be obtainable for the water-cement ratio of a fresh concrete sample by using the buoyancy principle.

## LABORATORY APPARATUS AND PROCEDURE

The following equipment is required to perform a test for the water-cement ratio of fresh concrete by the buoyancy principle:

1. An exact volume container with an evenly ground edge (a 0.010 ml [2.64 gal container was used).
2. A 20 to 30 kg (55 to 66 lb) capacity balance scale with 10 gm (0.4 ounce) readings and accuracy.
3. Stirrer or spatula for stirring the fresh concrete and water in Container 1.
4. Clear plastic plate for covering Container I and limiting its content to exactly 0.010 ml (2.64 gal).
5. Scoop or trowel to place the fresh concrete sample in Container 1.
6. Water connection with a hose or a container with approximately 0.010 ml<sup>3</sup> (2.64 gal) of water.
7. A container with a spout for adding small amounts of water.

An 11.0 kg (24.3 lb) sample of the fresh concrete is required to run this test for the water-cement ratio; and the bulk specific gravity (saturated surface-dry basis)  $\tilde{a}_a$ , absorption, and natural moisture content of the aggregate must be obtained accurately (ASTM C 127 and C 128)<sup>13,14</sup>.

The specific gravity of the cement  $\tilde{a}_{ct}$  is assumed to be 3.15 unless a more exact value is obtained from tests. The ratio of aggregate-to-cement by weight  $B$  must be determined. If pozzolan is used in the concrete, the specific gravity of the pozzolan  $\tilde{a}_p$ , and the ratio of pozzolan to cement by weight  $C$  must be known.

The test is performed in 11 steps, as follows.

1. Set balance scale, level, and tare.
2. Wet the container, plastic plate, and tare. This step is important because if the test begins with a dry container, the succeeding measurements would all deviate from the first. This occurs because at the second measurement the container is not dry any longer and weighs a little more. (Do not forget the plexiglass plate when taring).
3. Measure exactly 10.0 kg (22.0 lb) of fresh concrete  $w_c'$  into the container. Careful weighing is very important in this method. (Do not forget the plastic plate.)
4. Fill the constant volume container to approximately 0.5 cm (0.2 in.) below the rim with water.
5. Stir the concrete and water so that any entrapped and/or entrained air is removed. During this stirring, be careful that none of the container's content splashes out. After a vigorous stirring time of 1 to 2 min, the air is usually removed. No concrete residues should cling to the bottom of the container. Foam develops on the water surface during this step.
6. Fill the container with additional water to the rim, and remove any foam by sliding the stirrer across the container's rim. Here it is hard to avoid removing an insignificant amount of very fine particles with the foam.
7. Slide the plastic plate across the container's rim from one side so that the container is now filled with air-free water and concrete. If air bubbles are observed under the plastic plate, water must again be added and this step repeated.
8. Remove overflowed water from the container and scale.
9. Weigh the filled container and plastic plate  $w_t$
10. Determine the underwater weight of the concrete  $w_c$

$$w_c' = W_T - 10.0 \text{ kg (22.0 lb)} \quad (15)$$

The 10.0 kg (22.0 lb) value in the preceding equation is the weight of water that the constant volume container is capable of holding, since the container's volume is exactly 0.010 m<sup>3</sup> (2.64 gal). The weights of the plastic plate and constant volume container are accounted for when taring in an earlier step.

11. Using the obtained values, determine the water- cement ratio  $w_w/w_{ct}$ . Use Eq. (13) or (14). It is necessary to calculate the result to three decimal places and then round off to two decimal places.

If a 0.010 m<sup>3</sup> (2.64 gal) constant volume container is not available, any container of known volume and similar capacity may be substituted, providing that Eq. (15) is modified by the container's exact volume.

If taring is not convenient with the balance scale available, the weight of the plastic plate and constant volume container can be measured and subtracted from total weight values in Steps 2 and 10.

## PRESENTATION AND ANALYSIS OF LABORATORY DATA

City of Milwaukee room temperature tap water was used in the concrete sample batches. Type I cement was used, and its specific gravity was assumed to be 3.15.

Fineness modulus for the sand was determined by ASTM standard procedure after sieving for 10 min in an electrically driven sieve shaker. Three tests were run on the sand and the average value was used for mixture proportioning. The percent natural moisture values for the sands were obtained by drying three 1500 gm (3.3 lb) samples in their natural state to a constant weight in a microwave oven at full power (generally less than 15 min) and averaging the values obtained. Then the samples were allowed to cool in air for 30 min and weighed again. The difference between the starting weight and dried weight is the natural moisture in the sample. Natural moisture must be accounted for accurately to determine an accurate water-cement ratio. Bulk specific gravity (saturated surface dry basis) and percent absorption values were obtained by using modified ASTM C 128<sup>14</sup> tests. These tests were performed according to the ASTM standard except for the method of drying. A microwave oven was used instead of a conventional oven to dry the sample to a constant weight at full microwave power. Drying time for a sample was always less than 15 min. The samples were then allowed to cool in air for 30 min before the final dry weights were obtained. Samples of 250 to 500 gm (0.53 to 1.10 lb) were used in a volumetric flask for specific gravity values. It was found that large variations in absorption values were occurring when using these small samples. Therefore, 1400 to 2600 gm (3.1 to 5.7 lb) samples were used for obtaining absorption values. The test results were more consistent and specific gravity tests could be run simultaneously.

Maximum size 19 mm (3/4 in.) gravel was used. Dry-rodded unit weights for the gravel were obtained by standard procedure. Three tests were run and an average value was obtained. The percent natural moisture value for the gravel was obtained by drying three 1500 gm (3.3 lb) samples of gravel in their natural state to a constant weight in the microwave oven at full power and averaging the values. This generally took less than 15 min. Then the samples were allowed to cool in air for 30 min and again weighed. The difference between the starting weight and dried weight is the natural moisture of the sample. Bulk specific gravity (saturated surface dry basis) and percent absorption values were obtained by using modified ASTM C 127<sup>13</sup> tests. The tests were performed using all of the standard's procedures except for the method of obtaining an underwater weight and drying. The underwater weight of the gravel sample was obtained by using the buoyancy principle of Archimedes:<sup>12</sup> "A body wholly or partly immersed in a fluid is buoyed up with a force equal to the weight of the fluid displaced by the body." The saturated surface dry sample was weighed in a container of known volume. The container was then filled with water, stirred to allow any air bubbles to escape, and covered with a plastic plate (not allowing any air to remain inside). The constant volume container, water, gravel sample, and plastic plate were then weighed. This weight minus the weight of water that would fill the constant volume container, the container's weight, and the plastic plate weight yields the underwater weight of the gravel sample. The water was drained off and the sample of gravel dried in the microwave oven to obtain the sample's dry weight. A microwave oven was used to dry the sample to a constant weight at full power. Drying time for a 3000 to 6000 gm (7 to 13 lb) sample was always less than 20 min. The microwave oven was stopped briefly every few min and the sample stirred to help release any entrapped moisture. Weights were also recorded to

demonstrate the rate at which moisture left the sample. The samples were then allowed to cool in air for 30 min before the final dry weights were obtained.

Concrete mixture proportioning was done by the Bureau of Reclamation Procedure.<sup>15</sup> The amounts of aggregate were calculated by computing the total solid volume of sand and coarse aggregate in the concrete mix and multiplying by the recommended percentage of sand. Approximately 10 kg (22 lb) of concrete were required for performing the buoyancy test. However, 34 kg (75 lb) batches were made to provide for any additional tests to be made (air content,<sup>16</sup> etc.) and to provide for a more representative sample.

A tilting drum-type mixer was used to mix the concrete. Materials were mixed for 2 min and then half the amount of water required was added. Wet mixing was carried out for 45 sec and then fly ash, cement, and the remaining water were added. Mixing was continued for 2 min and 15 sec. The concrete mixture was then discharged onto a pan and turned over with a shovel before determining the properties of the fresh concrete.

Tests A-1 through A-8 were performed in a room with room temperature of  $23 \pm 2$  C ( $73 \pm 3$  F) and humidity of  $49 \pm 4$  percent. The batches used for Tests A-1 through A-8 are shown in Table 1 -

A correction for the natural moisture content of the aggregate was made by using the average natural moisture content value obtained earlier. This resulted in "actual" water-cement ratios that were different from the water-cement ratios planned in the mixtures of Table 1. This correction was made by calculating the effective water in the batch.

Table 1 – Base case mixture proportions

Test no.	1	2	3	4	5	6	7	8
<b>Contents</b>								
<b>Water, lb*</b>	<b>5.69</b>	<b>5.77</b>	<b>5.82</b>	<b>5.92</b>	<b>5.99</b>	<b>6.06</b>	<b>6.12</b>	<b>6.19</b>
<b>Cement, lb*</b>	<b>16.27</b>	<b>14.43</b>	<b>12.94</b>	<b>11.84</b>	<b>10.88</b>	<b>10.09</b>	<b>9.42</b>	<b>8.84</b>
<b>Sand at SSD, lb*</b>	<b>22.36</b>	<b>23.67</b>	<b>24.84</b>	<b>25.84</b>	<b>26.84</b>	<b>27.70</b>	<b>28.64</b>	<b>29.49</b>
<b>Gravel at SSD, lb*</b>	<b>30.68</b>	<b>31.13</b>	<b>31.40</b>	<b>31.40</b>	<b>31.29</b>	<b>31.15</b>	<b>30.82</b>	<b>30.48</b>
<b>Total sample weight, lb*</b>	<b>75.00</b>	<b>75.00</b>	<b>75.00</b>	<b>75.00</b>	<b>75.00</b>	<b>75.00</b>	<b>75.00</b>	<b>75.00</b>

\*1 lb. = 0.4536 kg.

'SSD = saturated surface dry

The effective water is the water available for hydration and is simply the total amount of water in the batch minus the amount of water absorbed by the aggregate in the saturated surface dry condition. Test results including the "actual" water-cement ratio are shown in Table 2 for Tests A-1 through A-8.

A correction for the moisture content of the aggregates was made in the buoyancy method calculations by adjusting the value for the relation of aggregate to cement by weight B. The water above that required for the saturated surface dry condition must be deducted from the aggregate weight.

Interestingly, the buoyancy principle yielded generally low results when compared to the known water-cement ratio of the sample. Note that the percent error generally decreased as the water-cement ratio increased. Of course, more tests would have to be performed before a pattern of this type could be validated. The average percent error for the buoyancy tests was six percent with a range from minus Fifteen percent to plus eight percent. Controlled tests were performed to determine the reasons for these errors and variations.

Three special tests were performed for the buoyancy principle to locate problems in this method. A 10.0 kg (22.0 lb) batch of concrete was made. The batch consisted of 4.62 kg (10.2 lb) of 3/4 in. (1.9 cm) gravel, 3.08 kg (6.79 lb) of sand, 1.54 kg (3.40 lb) of cement, and 0.77 kg (1.7 lb) of water. Separate smaller samples of sand and gravel were combined and dried in the micro-wave oven to determine very accurate natural moisture content. Hand-mixed batches were used for all tests. Table 3 shows the results of the three controlled tests. The test results show consistently higher values than previously known exact values. The buoyancy principle is very dependent on accurate weights of the sample both in and out of water, as well as accurate specific gravity values.

Specific gravity and percent absorption values for the aggregates were obtained from the supplier for comparison to experimentally obtained values as a part of this research. Table 4 shows the supplier's specific gravity and percent absorption values as compared to the experimentally obtained values. The supplier's values are substantially different and could result in substantially different water-cement ratios.

The aggregate's specific gravity and percent absorption values were used in the calculations for the controlled buoyancy test #1. The average specific gravity for the

Table 2 – Experimental test data

Water-cement ratio by weight			
Test no.	Actual	Buoyancy tests	Percent error
A-1	0.36	0.35	- 2.8
A-2	0.41	0.35	- 14.6
A-3	0.47	0.46	- 2.1
A-4	0.52	0.48	- 7.7
A-5	0.57	0.54	- 5.3
A-6	0.62	0.67	+ 8.1
A-7	0.68	0.70	+ 2.9
A-8	0.73	0.70	- 4.1

Table 3 – Controlled buoyancy principle test results

Test no.	Known water-cement ratio by weight	Water-cement ratio by the buoyancy principle		Percent error	
		Actual	Revised	Actual	Revised
1	0.49	0.54	0.52	+ 10.2	+ 6.1
2	0.49	0.54	0.52	+ 10.2	+ 6.1
3	0.49	0.54	0.52	+ 10.2	+ 6.1

Table 4 – Bulk specific gravity and absorption value comparison

	Supplier's values	Actual values	Percent difference
<b>¼ in. (19 mm) gravel at SSD condition*</b>			
Bulk specific gravity	2.71	2.67	1.5
Percent absorption	1.21	1.31	7.9
<b>Sand at SSD</b>			
Bulk specific gravity	2.66	2.71	1.9
Percent absorption	1.06	1.57	38.8

\*SSD = saturated surface dry

aggregate (based on the amounts of sand and gravel used) came out the same as the experimental average, 2.69. This was due to the variation in opposite directions of the experimental values when compared to the supplier's values (i.e., the experimental value for sand was higher and the experimental value for gravel was lower than the supplier's value [Table 41]). However, the percent absorption values obtained experimentally were higher than the supplier's values and yielded different results. The supplier's data brought the water-cement ratio from 0.54 to 0.52. This value is closer to the known value of the water-cement ratio, 0.49, but is still 6.1 percent error. Substantial differences in percent absorption values yielded only 0.02 difference in water cement ratio values. Specific gravity has a much greater effect on the water-cement ratio. If the average specific gravity value for the aggregates was 2.65 rather than 2.69, there would have been 0 percent error between the experimental and actual value for the water-

cement ratio. This further demonstrates the importance of accurate specific gravity and percent absorption values.

Table 5 – Special test series BB concrete batch proportions, lb\*

Test no.	Water, lb	Cement, lb	Sand, lb	Gravel, lb
BB-1	1.21	3.47	6.94	10.42
BB-2	1.38	3.44	6.89	10.33
BB-3	1.54	3.42	6.83	10.25
BB-4	1.62	3.39	6.78	10.18
BB-5	1.85	3.37	6.73	10.09
BB-6	2.00	3.34	6.68	10.02
BB-7	2.15	3.32	6.63	9.94
BB-8	2.30	3.29	6.58	9.87

  

Water-cement ratio by weight			
Test no.	Actual	Buoyancy	(Percent error)
BB-1	0.28	0.31	+ 10.7
BB-2	0.33	0.35	+ 6.1
BB-3	0.38	0.40	+ 5.3
BB-4	0.43	0.43	+ 0.0
BB-5	0.48	0.49	+ 2.1
BB-6	0.53	0.54	+ 1.9
BB-7	0.58	0.60	+ 3.4
BB-8	0.63	0.65	+ 3.2

\*1 lb = 0.4536 kg.  
Average percent error: 4.1 percent.

An additional eight controlled buoyancy tests (Special Test Series BE) were performed with oven-dry aggregate to verify the pattern developed in the three previously controlled buoyancy principle tests. Mixing was performed in the constant volume container. Table 5 shows the batches used and results obtained. The average percent error for the eight tests was 4.1 percent.

## CONCLUSIONS AND RECOMMENDATIONS

In reviewing the laboratory work and research performed, several conclusions and recommendations can be made.

A microwave oven can be used successfully to dry aggregates to a constant weight in much less time than the standard ASTM oven-drying procedure. The microwave method takes less than an hour (usually about 20 min), and conventional oven drying takes about 24 hr. Thus, the microwave oven can be used successfully to determine natural moisture contents, percent absorption values, and specific gravity values in short periods of time. Results obtained for bulk specific gravity, percent absorption, and natural moisture content values were similar to the supplier data for the aggregate analyzed.

The buoyancy principle has been used in various ways for analyzing the specific gravity of materials for decades. The buoyancy method makes the rapid analysis for the water-cement ratio of a fresh concrete sample possible by using this old principle.

The test can be performed rapidly, and test results demonstrate that extreme care is required. As discussed earlier, the buoyancy principle is very dependent on accurate specific gravity and absorption values.

The research performed demonstrated a pattern of consistently high or low values for sets of water-cement ratio tests. The controlled test sets yielded consistently high values where standard tests A-1 through A-8 yielded consistently low values for the water-cement ratio. Both sets of tests used the same specific gravity and percent absorption values. This conflict points to balance inconsistencies, natural moisture differences, the obtaining of a representative sample, or a combination of these problems. Further research was performed with the extreme accuracy to determine if any patterns do in fact exist. As shown in the Series BE tests, the accuracy was very significantly improved.

Whereas fly ash is being used more frequently as a partial cement substitute, the buoyancy equations have been mathematically developed for use on concrete containing fly ash. Knowledge of fly ash's specific gravity and ratio to cement is required to obtain the water-cement ratio of such concrete. Further research is recommended to demonstrate the practicality of the equation on concrete containing fly ash.

Of course the concrete supplier can be requested to supply batch tickets identifying how much of each ingredient was batched at the plant, and the water-cement ratio can be calculated from this information, provided the moisture content of the aggregate is known.<sup>17</sup> This computation is dependent on accurate scale readings, accurate aggregate moisture content information, and a good ready-mix truck operator (i.e., additional water should not exist in the mixer prior to loading and should not be added enroute to the construction site). The Buoyancy Method allows for a fast independent check of the water-cement ratio of fresh concrete for people who require close control or additional verification.

The Buoyancy Method is fast, simple to perform, inexpensive, and field-worthy. Continuing research will verify the accuracy of this ideal method and exhibit its value in quality control and quality assurance.<sup>18</sup>

The obtaining of a value for the water-cement ratio of fresh concrete in 15 min or less is vitally needed and rapidly becoming possible.

## REFERENCES

1. Naik, Tarun R., "Utilization of Accelerated Strength Testing Methods," *Cement and Concrete Research*, V.9. No. 1. Jan. 1979, pp. 7-18.
2. "Standard Test Method for Making, Accelerated Curing, and Testing of Concrete Compression Test Specimens," (AST.M C 684- 74), *1979 Annual Book of ASTM*
3. Naik. T. R., "Variations in Concrete Strength," presented at the ACI Annual Convention, San Antonio, Mar. 1987.
4. Blaut, Ing H., "Experience Gained from Measuring the Water- Cement Ratio According to the Thaulow Method," *Beionwerk Ferrigreeii-Technik* (Wiesbaden), No. 8, Aug. 1972, 8 pp.
5. Dunagan, M., "A Study of the Analysis of Fresh Concrete," *Proceedings*, ASTM, V. 31, Part 1. 1931, pp. 362-381.
6. Grimnauer, G. J., "A Substitute for the Compression Test of Concrete: A Method for Determining the Composition and Quality of Concrete While in Its Plastic State," *Engineering New-Record*, V. 103, No. 22, 1929, pp. 846-847.
7. Kelly, R. T., and Baldwin, P. J., "The Kelly-Vail Technique for Water and Cement Content," *Rapid Testing of Fresh Concrete*, Conference Proceedings M-128, U.S. Army Construction Engineering Research Laboratory, Champaign, May 1975, pp. 19-41.
8. S. Peterson. Robert T., and Leftwich, Dave. "Determination of Water Content of Plastic Concrete Using a Microwave Oven," *Final Report*, Materials and Research Division, North Dakota State Highway Department, Bismark, Sept. 1978, 20 pp.
9. Howdvsheil. Paul A., "Concrete Quality Control: 28 Days-24 Hours- 1 5 Minutes," *Accelerated Strength Testing*, SP-56, American Concrete Institute, Detroit, 1978, pp. 183-200.
10. Popovics, Sandor, "Determination of the Composition of Fresh Concrete by Non-Nuclear Means," *Rapid Testing of Fresh Concrete*, Conference Proceedings M-128, U.S. Army Construction Engineering Research Laboratory, Champaign, May 1975, pp. 5-18.
11. Rhodes. 1. R., "History of Nuclear Methods," *Rapid Testing of Fresh Concrete*, Conference Proceedings.M-128, U.S. Armv Construction Engineering Research Laboratory, Champaign, May 1975, pp. 83-104.
12. Halliday, David, and Resnick, Robert, *Fundamentals of Physics*, John Wiley & Sons, New York, 1970, p. 282.
13. 'Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate," (ASTIM C 127-77). *1979 Annual Book of ASTM Standards*, Part 14, ASTM, Philadelphia, pp. 77-80.
14. "Standard Test Method for Specific Gravity and Absorption of Fine Aggregate," (ASTM C 128-73), *1979 Annual Book of ASTM Standards*, Part 14, ASTM, Philadelphia, pp. 81-83.
15. *Concrete Manual*, 8th Edition, U.S. Bureau of Reclamation, Denver, 1975, pp. 627

16. "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method," (ASTM C 173-78), *1979 Annual Book of ASTM Standards*, Part 14, ASTM, Philadelphia, pp. 123-125.
17. Mather, Bryant, "How Soon is Soon Enough?," *ACI JOURNAL, Proceedings V.* 73, No. 3, Mar. 1976, pp. 147-150.
18. Ramme, Bruce W., "A P.D.Q. Method of Determining the Water-Cement Ratio of Fresh Concrete," MSc thesis, University of Wisconsin, Milwaukee, Aug. 1980. 125 pp.