ciency of Deformed Concrete Reinforcing Bars," *Proceedings*, ACI, Vol. 43, pp. 381–400, December 1946.
4. "Use of Air-Entraining Concrete in Pavements and Bridges," Current Road Problems No. 13, Highway Research Board, May 1946.
5. Cordon, W. A., "Entrained Air—A Factor in the Design of Concrete Mixes," ACI, Vol. 42, pp. 605–20, June 1946.
6. Gonnerman, H. F. and Shuman, E. C., "Flexure and Tension Tests of Plain Concrete," PCA Report of the Director of Research, November 1928.
7. Menzel, C. A., "Some Factors Influencing Results of Pull-Out Bond Tests," ACI, Vol. 35, pp. 517–544, June 1939.
8. Menzel, C. A., "A Proposed Standard Deformed Bar for Reinforced Concrete," 17th Semi-Annual Meeting, Concrete Reinforcing Steel Institute, September 1941.
9. "Hi-Bond Reinforcing Bar," Tests by F. E. Richart, Published by Inland Steel Company.
10. Abrams, D. A., "Tests of Bond Between Concrete and Steel," Univ. of Ill. Eng. Exp. Sta. Bulletin 71, 1913.
11. Emperger, F., "Die Wirkung der Endhaken im Eisenbeton," Beton u. Eisen, Vol. 34, pp. 197–200, June 20, 1935.
12. Dunagan, W. M. and Ernst, G. C., "An Experimental Study of Bond Stresses," *Proceedings*, HRB, Vol. 16, pp. 96–99 (1936).
13. Watstein, D., "Bond Stress in Concrete Pull-Out Specimens, *Proceedings*, ACI, Vol. 38, pp. 37–50, September 1941.
14. Watstein, D., "Distribution of Bond Stress in Concrete Pull-Out Specimens," *Proceedings*, ACI, Vol. 43, pp. 1041–1058, May 1947.
15. Edwards, L. N. and Greenleaf, H. L., "Experimental Tests of Concrete-Steel Bond," *Proceedings*, ASTM, Vol. 28 II, pp. 584–604, 1928.

WASHINGTON METHOD OF DETERMINING AIR IN FRESH CONCRETE

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SYNOPSIS

Among the methods developed for the determination of air in fresh concrete, the pressure method has many advantages. The Washington method is an adaptation of the pressure principle in a manner which differs from that commonly employed. A chamber containing air is connected through a valve to a sample of concrete in a sealed container. With the valve closed, air is forced into the chamber to a measured gage pressure. When the connecting valve is opened, the gage pressure on the system drops to a value dependent on the air content of the concrete.

Advantages of the method are:

1. In common with other pressure methods, no weight determinations are needed and the percentage of air in the sample can be read directly.

2. Compared to other pressure methods, the apparatus is more compact, determinations are made more rapidly, no water is used in the test, corrections are not needed under varying barometric pressures, and calibrations can be made readily in the field over the full usable range of air contents.

Construction of the device and auxiliary apparatus is illustrated. Test data show it to be accurate. The operation is easily understood and has been used successfully by inspectors on construction work without personal instruction.

A rapid increase in the use of air entrainment in concrete during the past few years has given rise to extensive studies of methods of determining the air content of fresh concrete. Among the methods that have been developed, the pressure method has been found, in general, to be the most suitable with respect to convenience and speed. With most aggregates, it yields results of adequate accuracy. This paper describes a method that differs in principle from other pressure methods and which is considered to have advantages in simplicity and speed of operation.

REVIEW OF TEST METHODS

The oldest method that is suitable for field use is the gravimetric method, ASTM Designation C 138-44. In this method, the theoretical unit weight of the concrete is calculated from the specific gravities and batch weights of the constituent materials. The actual unit weight is determined by weighing a known volume of the mixed concrete. The air content is calculated from these values. Accuracy by this method requires precise determination of unit weight, batch proportions and specific gravities of cement and aggregates. These requirements plus involved calculations make the method not well suited for field use. Additional discussion of this method will be found later in this report.

In the drop-in-unit-weight method, unit weights are determined in concrete with and without air-entraining agents. The difference in unit weights is a measure of the air entrained as a result of using an air-entraining agent. The air content of the original concrete is not determined and hence the total air in the air-entrained concrete is not known. The method is less complicated than the ASTM gravimetric method but it requires a series of unit weight determinations and necessitates making fairly accurate weighings.

The Indiana method is an adaptation for field use of a volumetric laboratory method, ASTM Designation: C 173-42T. It requires relatively precise weighings and involved calculations and is difficult of application on the job.

Methods have been developed recently which eliminate all weighings and thus have a marked advantage over those previously described. Methods of this type have been investigated and described by Menzel (*1*) (*2*)[1].

In the "rolling" method, a definite volume of concrete is inundated with water and stirred or rolled until all air has been displaced. Loss of air causes a shrinkage in total volume which is measured either directly or by the measured addition of liquid to restore the original volume. Considerable foam is produced in the rolling or stirring process and this must be removed or destroyed for accurate measurement. Considerable time is required in rolling or stirring and, in general, the process must be repeated one or more times to make sure that complete removal of air has been accomplished.

The pressure method is based on the discovery by Klein and Walker (*3*) that the finely dispersed particles of air in fresh concrete respond to changes in pressure in accordance with Boyle's law. Inaccuracies may arise when incompletely saturated porous aggregates are used, due to decrease in volume of air within the particles under pressure. Except with highly porous aggregates such as slag, pumice or burnt clay, a correction can be applied by making pressure tests of samples of the aggregates alone. A number of devices are on the market which make use of the pressure method. As far as known, all operate on the following principle:

A container of known volume is filled with concrete and struck off flush with the top. A cover in the shape of a truncated cone with a tubular extension and graduated transparent tube is clamped to the container. Water is introduced until the assembly is full to the zero mark on the tube. Air pressure is applied above the water to the desired amount as indicated by a pressure gage. Decrease in volume under pressure is observed on the calibrated tube which can be made to indicate percentage air in the concrete directly. Menzel (*1*) (*2*) has described a method of calibration. New calibrations or corrections must be made for use under marked changes in atmospheric pressure such as occur under changes in elevation above sea level of several hundred feet. Menzel states that a test can be completed within about 8 minutes after the concrete has been struck off in the container. Check readings can be made by releasing and again applying pressure.

WASHINGTON METHOD

Experiments conducted in the laboratory of the Washington Department of Highways have led to the development of a pressure method, based on Boyle's law, which is performed in a more compact device than that described above since a calibrated tube is not needed.[2] No water is used in the test. This

[1] Italicized figures in parentheses refer to a list of references at the end of the paper.

[2] It has been learned recently that R. P. Vellines, Research Laboratory, Universal Atlas Cement Co., also conceived and has constructed a similar device.

simplifies its use in the field. It is of advantage in laboratory work in that no change is made in the concrete during testing and the sample can be returned to the batch for other tests.

Imagine a closed container of known volume, V_1, containing air under atmospheric pressure, P_a, and connected by a valve with a second chamber of unknown volume, V_2, likewise containing air under atmospheric pressure. With the connecting valve closed, force air into the first chamber until the pressure becomes P_1. Open the valve. The pressure will drop to a new value, P_2. The volume of the second chamber, V_2, can then be computed by Boyle's law as follows:

$$V_2 = \frac{V_1(P_1 - P_2)}{P_2 - P_a} \quad (1)$$

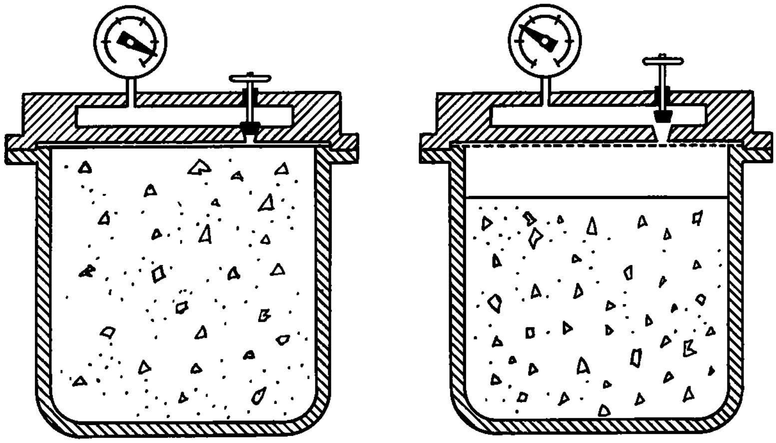
In this formula, P_1 and P_2 are absolute pressures, that is they represent the sum of the gage pressure and the barometric pressure. The derivation of this formula is given in Appendix A of this report. It is shown there that barometric pressures cancel each other and that formula (1) may be written

$$V_2 = \frac{V_1(G_1 - G_2)}{G_2} \quad (2)$$

in which G_1 and G_2 represent gage pressures corresponding to the absolute pressures P_1 and P_2. This means that, in using devices constructed according to this principle, no account need be taken of the prevailing barometric pressure. The device calibrated at sea level, for example, can be used at high elevations without applying a correction factor.

In the Washington air meter, the unknown volume of air in a sample of concrete (of known volume) is represented by V_2 in equation (2).

Preliminary tests in a crudely constructed apparatus indicated the method was capable of yielding accurate results. Apparatus similar to that shown schematically in Figure 1 was then constructed.



After the pot is filled with concrete, the cover is clamped on, the connecting valve is closed and the pressure is applied to the air chamber.

When the connecting valve is opened, pressure compresses the concrete in proportion to its air content and the gage pressure drops accordingly.

Figure 1. Illustration of Test Method

The pot ($\frac{1}{4}$ cu. ft. in volume) is filled with concrete and struck off, first with a board then with a glass plate. The cover which is clamped in place contains a chamber having a volume of about 20 cu. in. (accurately determined by test). A valve seated in the bottom of this chamber, but operated from the top of the cover, opens or closes an orifice leading to the concrete sample. The cover is also fitted with a tire valve and a pressure gage. In operation, the connecting valve is closed and pressure is applied to the chamber with a tire pump. The gage reading is observed.

The connecting valve is opened and the new gage reading is noted. Sufficient data have now been obtained to compute the volume of air in the concrete by means of equation (2).

In operating this device a number of refinements in design were indicated and subsequently incorporated. The flange of the container at first was flush with top. This interfered with striking off the concrete and the flange was difficult to wipe sufficiently clean to permit a tight seal when the cover was clamped in place. The flange was then dropped about ⅜ inch below the rim of the container with considerable improvement in ease of operation. The thickness of the gasket was adjusted so that, when clamped, the bottom of the cover would be in contact with the rim of the container, thus eliminating any space above the concrete. It was found very difficult to clean the rim and keep it free from particles while attaching the cover. Unless the rim was absolutely clean, the gasket would not be compressed sufficiently to form a tight seal. Stops were then placed on the cover which provided a clearance of about 0.02 in. between the cover and the rim, thus providing a fixed air space of known volume which was subtracted from the indicated volume of air in the concrete. The gasket was designed so that it would be compressed sufficiently under these conditions to afford a tight seal.

A gage with a 4½-in. dial and a capacity of 15 psi. which can be read to 0.1 psi. was found suitable for indicating pressures. The computation of percentage air in the concrete, while not unduly laborious, required more time than desirable. It was possible to calibrate the gage to read percentage air in the concrete directly, provided the initial pressure was always adjusted to the same value. A needle valve was attached to the cover, which permitted bleeding excess air to the desired initial point corresponding to 14 psi. This valve also afforded a convenient means of releasing pressure from the system so that check readings could be obtained readily.

The decision to design the meter with a capacity of ¼ cu. ft. of concrete was based on the work of Menzel (*1*) who found that accuracy of determining air content was substantially as good with a concrete sample of 0.22 cu. ft. as with a volume twice as great. The first model was made of steel. A subsequent model was made of cast bronze. Cast magnesium has been used in all later models.

Figure 2 is a view of the assembled meter, together with auxiliary parts and a carrying case. When made of cast magnesium, the assembled meter weighs 17 lb., the pot alone, 9 lb., and the pot filled with concrete about 46 lb. The case and all parts, including a spare glass plate, weighs 44 lb.

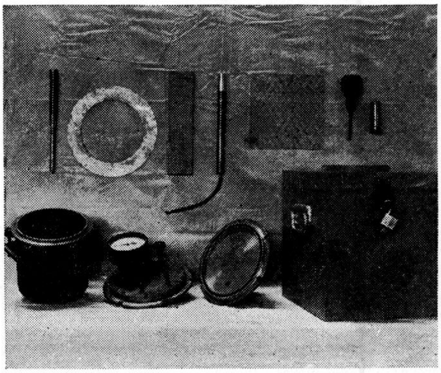


Figure 2. Parts of Washington Air Meter

Upper Row (left to right). ⅝ by 14-in. tamping rod; shield to collect surplus concrete during strike-off; board for preliminary strike-off; bicycle pump; glass plate for final strike-off; syringe for withdrawing water during calibration; calibration cup with capacity equal to one percent of volume of pot.

Lower Row (left to right). Pot; cover showing (clockwise) pressure gage, connecting valve, needle valve and tire valve; bottom of cover showing gasket and seat of connecting valve; carrying case.

CALIBRATION

The volume of the chamber in the cover can be determined by measuring the amount of water required to fill it. A threaded plug in the side of the cover is removed for introduction of water. The free space between the cover and the surface of the concrete can be computed from accurate measurements, thus permitting computation of the volume of air within the concrete.

Actually it has been found to be more satisfactory to calibrate and graduate the gage (fitted with a blank dial) by the following procedure:

The container is filled with water and struck off flush with a glass plate, first making sure that the rim is exactly level. The cover is clamped on. With the connecting valve closed, pressure is applied and adjusted to the initial mark (corresponding to 14 psi.). The connecting valve is opened and the gage needle drops to a point representing zero percent air in the concrete. The cover is removed and a measured amount of water corresponding to 1 percent by volume of the container is withdrawn with a syringe. The calibration procedure is then repeated to establish a point on the gage corresponding to 1 percent air. The gage is thus calibrated over a suitable range of air contents usually up to 7 percent. The scale of graduations on the gage is not linear but intermediate graduations can be computed arithmetically. A 4½-in. dial provides sufficient space to permit graduations of 0.2

TABLE 1

TEST OF AIR METER BY WATER REPLACEMENT

Volume of chamber in cover, V_1, 19.05 cu. in.
Volume of pot, 428 cu. in.
Pot exactly filled with water and measured increments withdrawn.
Initial pressure, G_1, adjusted to 14 psi. in all cases.
Volume beneath cover and above rim of pot, 3.15 cu. in.

Water Removed from Pot		Final Pressure G_2	Volume beneath Cover[a] V_2	Net Volume of Air in Pot by Test		Difference
cu. in.	%	*psi.*	*cu. in.*	*cu. in.*	%	%
0	0.00	12.00	3.18	0 03	0.01	0.01
6.10	1.42	9.40	9.32	6.17	1.44	0.02
12.20	2.86	7.75	15.37	12.22	2.85	0.01
15.25	3.57	7.15	18.25	15.10	3.53	0.04
18.30	4.28	6.60	21.37	18 22	4.25	0.03
21.35	4.99	6.10	24.67	21 52	5.04	0.05
24.41	5.70	5.75	27.34	24.19	5.65	0 05
27.46	6.41	5 35	30.80	27 65	6.46	0.05
30.51	7.14	5.10	33.24	30 09	7.05	0 09
33.56	7.83	4.80	36 52	33 37	7.81	0.02

[a] Calculated by Equation $V_2 = \frac{V_1 (G_1 - G_2)}{G_2}$

percent between 0 and 5 percent air and of 0.5 percent between 5 and 7 percent air. The air content can be estimated readily to the nearest 0.1 percent.

A potential source of error exists in the solubility of air in water under increasing pressure. It has been found, however, that error from this source is not important, presumably because of the slow rate of absorption of air under the conditions of test. The temperature of the water in the container should be close to room temperature to avoid volume changes in the water due to change in temperature.

EXPERIMENTAL DATA

Table 1 gives the results of calibration with water against pressure gage readings in pounds per square inch. For all percentages of air up to eight, the volume computed from test data differed from the actual volume by less than 0.1 percent.

A number of series of laboratory-made batches of concrete were tested for air content by the air meter and by the gravimetric method ASTM C 138–44. The unit weight of the concrete, required in the latter test method, was made on the sample of concrete after determination by the air meter. In each series, the percent air by meter was consistently higher than by the gravimetric method, the differences being from 0.5 to 1.5 percent. In each succeeding series, increased refinement was used in determining values of specific gravities and weights of materials in the batch. These steps did not bring the results by the two methods into closer agreement. The possibility that the aggregates contained air voids which might increase the apparent air content of the concrete was investigated. It was found that there was no measurable effect from this cause.

The batches were from ½ to 1 cu. ft. in volume and were mixed in a Lancaster mixer. It was concluded that the cause of the discrepancy was in inability to transfer a truly representative sample into the pot of the air meter and that the sample thus taken were always slightly high in coarse aggregate and low in mortar.

The following calculation shows the effect of a sample containing 5 percent more coarse aggregate than is in the batch. Assume the following batch:

		lb.		*cu. ft.*
gravel.		71.96		.4285
mortar				
sand	52.29		.3136	
cement	21.32		.1073	
water.......	9.40		.1506	
		83.01		.5715
		154.97		1.0000

If the above mixture contains 3 percent air it will weigh 0.97 × 154.97 = 150.32 lb. per cu. ft. and its composition will be:

	lb.	*cu. ft.*
gravel....	69.80	.4156
mortar.	80.52	.5544
air.....		.0300
	150.32	1.0000
weight of gravel per cu. ft. (absolute)		167.94 lb.
weight of air-entrained mortar per cu.ft.		137.78 lb.

If the sample taken for test from the above batch contains 5 percent excess gravel its composition will be:

	lb.	*cu. ft.*
gravel...	73.29	.4364
air-entrained mortar....	77.65	.5636
	151.94	1.0000

The percent of air found by ASTM Method C 138-44 will be:

$$100 \times \frac{154.97 - 151.94}{154.97} = 1.96$$

The error in the gravimetric determination is:

$$3.00 - 1.96 = 1.04 \text{ percent}$$

On the other hand, the determination by air meter will be:

$$\frac{.5636}{.5844} \times 3 = 2.90$$

The error in the air meter determination is only

$$3.00 - 2.90 = 0.10 \text{ percent}$$

Craven (*4*) determined the air content of a series of concrete mixes by gravimetric and pressure methods and found the former to yield relatively inconsistent results which, in general, were lower than those obtained by the pressure method.

In one series, the air content by the pressure method was determined with a meter of the Klein-Walker type as well as with the Washington meter. The results of these tests are given in Table 2. They show that, while differences of 0.3 to 0.4 percent air were found in a few cases, the two meters give substantially the same results.

Meters of both types have been used on a construction project with excellent agreement. In these tests the Washington meter was found to be considerably faster in operation. As a rule, three gage readings of the same sample were obtained before filling of the Klein-Walker meter with water was completed.

Washington air meters have been used by inspectors on construction work without instruction other than that given in writing. No difficulty has been experienced in the operation of the device and results have appeared to be consistent.

CONCLUSIONS

The Washington air meter measures the air content of fresh concrete with a degree of accuracy well within the requirements of a field control method. It is simple and rugged in construction. No weighings are necessary. Percentage of air is indicated directly on a dial gage. Check readings of the gage can be made rapidly on the same sample of concrete. The device can be calibrated readily over the entire usable range with simple apparatus that can be used in the field.

Variations in barometric pressure do not affect its accuracy. A calibration made at one location will be accurate at other localities of different elevation above sea level.

TABLE 2
TESTS FOR AIR CONTENT BY TWO METERS OF PRESSURE TYPE

Batch No.	Percent Air		
	Klein-Walker	Washington	Difference
1	2.75	2.60	0.15
2	3.85	3.83	0.02
3	5.55	5.13	0.42
4	2.35	2.40	0.05
5	2.60	2.30	0.30
6	2.65	2.70	0.05
7	2.75	2.40	0.35
8	3.35	3.45	0.10
9	4.30	4.50	0.20
10	5.55	5.30	0.25
11	6.45	6.43	0.02
12	7.20	7.20	0.00
Average. ..	4.11	4.02	0.16

No water is required in making the test. This fact simplifies its use in the field. It is of advantage in laboratory work in that no change is made in the concrete during testing and the sample can be returned to the batch for other tests. Thus, it is not necessary to increase the size of batch in order to determine air content in addition to making other tests.

REFERENCES

1. Menzel, Carl A., "Development and Study of Apparatus and Methods for the Determination of the Air Content of Fresh Concrete." *Journal*, American Concrete Institute, May, 1947, *Proceedings*, Vol. 43, p. 1053.
2. Menzel, Carl A., "Procedures for Determining the Air Content of Freshly-mixed Concrete by the Rolling and Pressure Method." *Proceedings*, American Society for Testing Materials, Vol. 47, p. 833 (1947).

3. Klein, W. H. and Walker, Stanton, "A Method for Direct Measurement of Entrained Air in Concrete." *Journal*, American Concrete Institute, June, 1946, *Proceedings*, Vol. 42, p. 657.
4. Craven, M. A., "Sand Grading Influence on Air Entrainment in Concrete." *Journal*, American Concrete Institute, Nov., 1948, *Proceedings*, Vol. 45, p. 205.

APPENDIX A

Derivation of Equation for Computing percentage Air in Concrete from data obtained with Washington Air Meter.

Let V_1 = Volume of air chamber and connections.

V_2 = Volume of air in the concrete plus that in space between surface of concrete and bottom of cover.

P_1 = Absolute pressure on air chamber before opening connecting valve.

P_a = Absolute pressure on concrete, i.e. barometric pressure.

h = Pressure on entrained air due to head of concrete.

P_2 = Absolute pressure on whole system after connecting valve is opened,

By Boyle's law:

$$V_1P_1 + V_2(P_a + h) = V_1P_2 + V_2(P_2 + h)$$

$$V_1P_1 + V_2P_a + V_2h = V_1P_2 + V_2P_2 + V_2h$$

$$V_1P_1 - V_1P_2 = V_2P_2 - V_2P_a$$

$$V_1(P_1 - P_2) = V_2(P_2 - P_a)$$

$$V_2 = \frac{V_1(P_1 - P_2)}{P_2 - P_a} \qquad (1)$$

Let G_1 and G_2 = gauge pressures corresponding to P_1 and P_2

$$P_1 = P_a + G_1$$

$$P_2 = P_a + G_2$$

Equation (1) may be written

$$V_2 = \frac{V_1(P_a + G_1) - V_1(P_a + G_2)}{P_a + G_2 - P_a}$$

$$V_2 = \frac{V_1(G_1 - G_2)}{G_2} \qquad (2)$$

Volume of air in the concrete equals V_2 minus the volume of the space between the surface of the concrete and the bottom of the cover.

DISCUSSION

PAUL KLIEGER, *Associate Engineer, Portland Cement Association*—The authors are to be commended for their excellent paper describing a unique pressure apparatus for determining the air content of freshly-mixed concrete.

The air content of freshly-mixed concrete has been determined in the Research Laboratories of the Portland Cement Association for a number of years. The pressure type apparatus described by Carl A. Menzel (*1*) has been used. It was found that for most aggregates it is necessary to apply a correction factor for air contained in the aggregate in order to obtain the correct result for entrained air in the concrete. While this aggregate correction factor is relatively constant for materials from any one source, it will range from a negligible value to as much as 1.5 percent, or more, for natural aggregates from different sources. With slag aggregate it may be even higher. A method of determining the aggregate correction factor with the Washington apparatus will be described in this discussion.

The Menzel apparatus and the Washington air meter operate on slightly different principles. The Menzel apparatus operates at a constant pressure for the entire range of air contents. The working pressure, about 7.5 lb. per sq. in., is predetermined in the calibration of the apparatus. The Washington meter operates on a variable pressure principle. The air in the cell is pumped up to a pressure of about 14 lb. per sq. in. A valve is then opened to transfer this air pressure to the concrete in the pressure vessel. The air pressure in the cell then decreases in proportion to the air content of the concrete. The pressure gage is graduated to indicate this decrease in pressure directly in terms of percent air content of the concrete, including that contained in the aggregate. The graduation of the pressure gage is determined in the calibration of the apparatus and can be checked by subsequent tests. While this procedure is suitable for determining the air content of the concrete it is not entirely suitable for determining the aggregate correction factor.

The aggregate correction factor should be determined at a pressure approximately the same as the final pressure to be encountered in the test of the concrete. The air in the aggregate is contained in a complex system of pores and capillaries and responds differently at different pressures. The correction factor increases with increasing applied pressure as shown in a previous paper by Swanberg and Thomas (*2*) and as shown further by a series of tests described below.

A series of concretes were prepared using aggregates having different correction factors. The air contents of the concretes and the aggregate correction factors were determined with both the Menzel and the Washington apparatus. Two different methods were used to determine the aggregate correction factor with the Washington meter. In the first method, the aggregate was placed in the container, the container was completely filled with water and the correction factor was determined at a final pressure of approximately 14 lb. per sq. in. In the second method, the same procedure was followed except that a volume of water, equivalent to 3.0 percent of the volume of the container, was removed from the container prior to making the test. In this case, the correction factor was determined at a pressure equivalent to the final pressure that would result in testing a sample of concrete having a net air content of 3.0 percent. The aggregate correction factor was the gross percentage reading on the pressure gage minus 3.0 percent.

The results obtained, for the aggregate correction factor and the air content of the freshly-mixed concretes, with the two different types of apparatus, are shown in the Table A. Each value is the average of two tests made on different days.

The gross air contents determined by the Washington meter check well with those determined by the Menzel indicator. In all cases, the gross air contents were lower for the Washington air meter, the differences in the percent of air ranging from 0.09 to 0.21. For the Washington meter, the aggregate correction factors determined by the first method (container filled with water) were considerably higher than those determined by the second method (container minus 3 percent water). Applying the aggregate factors determined by the second method to the gross air contents determined with the Washington meter, gives net air contents which compare favorably with those determined by the Menzel indicator.

TABLE A

Aggregate Combination	Cement Cont.	Net W/C	Slump	Gross Air Content		Aggregate Correction Factor			Net Air Content		
				PCA	Washington	PCA	Washington		PCA	Washington	
							1st Meth	2nd Meth.		1st. Meth.	2nd. Meth,
	sk per cu yd.	*gal. per sk*	*in.*	%	%	%	%	%	%	%	%
1	6.2	4.5	1.7	4.12	4.03	0.38	0.59	0.27	3.74	3.44	3.76
2	6.0	5.0	2.8	5.11	4.90	0.12	0 17	0.03	4.99	4.73	4.87
3	6.4	4.6	4.2	5.57	5.40	0.79	1.07	0.74	4.78	4.33	4.66
4	6.1	6.4	1.5	2.57	2.47	0.46	0.52	0.38	2 11	1.95	2.09

The results show that the aggregate correction factor can be significant in amount. It should always be determined in order to obtain the correct percentage of entrained air in the concrete. With the Washington air meter, it should be determined at approximately the same final pressure as that obtained in the test of the concrete. This can be done by removing a volume of water from the vessel, approximately equivalent to the volume of air in the concrete, prior to making the test for the aggregate correction factor. The cup used for calibrating the apparatus can be used for removing this volume of water.

When proper correction is made for air contained in the aggregate, the Washington air meter is suitable for determining the air entrained in freshly-mixed concrete, over the range of air contents from 0 to 7 percent for which it was designed.

REFERENCES

1. Carl A. Menzel:
   (1) "Development and Study of Apparatus and Methods for the Determination of the Air Content of Fresh Concrete;" Bulletin 16 of the Portland Cement Association; reprinted from Journal of the American Concrete Institute (May 1947); Proc., v. 43, p. 1053, 1947.
   (2) "Procedures for Determining the Air Content of Freshly-Mixed Concrete by the Rolling and Pressure Methods;" Bulletin 19 of the Portland Cement Association; reprinted from Proc., American Society for Testing Materials, v. 47, p. 833–864, 1947.
2. John A. Swanberg and T. W. Thomas, "The Measurement of Entrained Air in Concrete," Proc. American Society for Testing Materials, v. 47, p. 869, 1947.

Bailey Tremper and W. L. Gooding, *Closure*—Mr. Klieger's discussion of the aggregate correction factor is a worthwhile contribution to the use of the Washington air meter. The necessity of applying the factor with some aggregates is clearly indicated. The method of determining the correction factor proposed by Mr. Klieger appears to be sufficiently precise for most purposes.

DURABILITY OF PORTLAND CEMENT CONCRETE DETERMINED BY PRIMARY DIRECTIONAL FREEZING AND UNIFORM THAWING

R. E. Bollen, *Testing Engineer, Nebraska Department of Roads and Irrigation*

SYNOPSIS

This report describes a freezing and thawing apparatus and a method of test for freezing 3- by 4- by 16-in. concrete beams primarily from one surface.

An automatic freezing and thawing cabinet similar to a commercial locker plant quick-freeze cabinet was equipped with horizontal freezer plates. Concrete beams were placed directly on the freezer plates and frozen. Thawing of the beams was accomplished by the introduction of steam into a system which continuously circulated air over the beams in the cabinet. The maximum temperature of the air was 70 F. during the thawing cycle, and the minimum plate temperature during the freezing cycle was −30 F.

Time-temperature relations are presented for 3-by 4-by 16-in. concrete beams in direct contact with the plates and also with the beams located at different heights above the plates. The investigation developed a freezing and thawing test in which five cycles of primary directional freezing and uniform thawing were produced each day.

The effect of primary directional freezing on 3- by 4-by 16-in. concrete beams cured for 7 days and also for beams cured for 28 days are shown. Length change, sonic modulus, flexural strength, and compressive strength were determined at five cycle intervals.

The data indicate that the primary directional freezing and uniform thawing is a rapid and severe test and that more uniform results can be obtained by using beams which have been cured for a minimum of 28 days, than by beams which have been cured only 7 days.

This paper covers a portion of an investigation of a method of test for determining the soundness of concrete prisms by primary directional freezing and uniform thawing. Most conventional methods of freezing and thawing tests of concrete specimens follow a procedure in which the change in temperature of the specimen proceeds fairly uniformly from all of the outside surfaces of the specimen toward the center of gravity of the smallest cross-sectional area. This procedure duplicates the direction of the change in temperature of