Illinois Develops High Pressure Air Meter for Determining Air-Content of Hardened Concrete

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This paper describes the development of apparatus and test procedure for determining air content of hardened concrete, utilizing pressure and the principles of Boyle's Law. The method has been found to be a valuable addition to the procedure for control of the production of concrete, and furthermore offers excellent promise for the determination of voids in bituminous concrete specimens.

For satisfactory penetration of the pressure to the entrained air, the specimens must be oven-dried and saturated immediately prior to testing. A test pressure of 5000 psi., the design capacity of the apparatus, was found satisfactory and better adapted to concrete of all air contents than lower pressures. The apparatus was built especially for routine testing of cores drilled from newly constructed pavements, but the size of the test specimen does not appear to be a noteworthy factor in determination of the air content, except that relatively thin pieces of concrete appear to show slightly lower air contents than cylindrical specimens.

Good reproducibility of air contents are obtained in independent tests of the same specimens at different ages, and the method provides excellent differentiation between concretes of different air contents. However, the air contents obtained generally are a little higher than those obtained for the same concrete in plastic state. This is believed to be due, at least partly, to the compressibility of the concrete specimens under the high pressure, which would register on the indicator as entrained air. At present, the air contents determined are corrected for this deviation, but an attempt will be made to include the compressibility of the concrete in a recalibration of the apparatus.

A reasonably satisfactory agreement was found between air contents of cylindrical specimens determined with the apparatus and air contents determined subsequently by microscopic means. Air contents of plastic concrete can be determined with good accuracy in the high pressure apparatus, which is taken as a general indication of the soundness of the method.

Though the experimental work by no means is considered completed, the apparatus has been used during the last two years, with apparently good results, for routine determinations of the air contents of cores drilled from the pavements.

● THE problem of determining the air content of hardened concrete by the pressure method was first considered by the Illinois Division of Highways in 1947 subsequent to the development of the air meter used for determining air contents of plastic concrete. This apparatus was used in a few exploratory tests in an attempt to determine the air contents of hardened concrete cylinders held under the constant pressure of 15 psi. for periods up to eight hours. While the results obtained obviously represented only a small part of the air content of the concrete, they nevertheless indicated the possibility that a sufficiently increased pressure might penetrate the air voids and accurately measure the amount of entrained air.

In 1948, the use of air-entrained concrete, with a minor exception, was extended to all types of construction in Illinois and, during the ensuing years, it was occasionally observed, particularly on pavements where salt had been used for removal of ice, that the desired resistance of the concrete was not being obtained in all instances. In the study of this condition, in which the Portland Cement Association cooperated by determining the air content of drilled cores by the traverse method, it was determined that the part of the pavements that had become damaged by the salt did not contain entrained air. It further appeared from the pattern of the occurrence of the surface damage, that the lack of entrained air generally was due to failure to replenish the supply of air-entraining solution toward the end of a day's run.

In order to keep contractors and its own inspectors alert to the necessity of constant vigilance to assure adequate air-entrainment, it seemed indispensable that the Illinois Division of Highways procure equipment whereby the air content of the concrete could be determined on a part of the cores regularly drilled from the pavements for checking the thickness of the slab and the compressive strength of the concrete. However, before deciding to obtain equipment for accomplishing this by microscopic means, it was decided to further explore the practicability of using high pressures and the principle applied in determining the air contents of plastic concrete.

Some preliminary work was performed in which a hydraulic cylinder with a bore of 1½ inches was used in testing small mortar bars. The pressures used ranged up to 4000 psi., and the results obtained were sufficiently encouraging to warrant the design and construction of an apparatus capable of testing full size cores as drilled from the pavements.

The principle involved is the same as in the design and use of the air meter employed in connection with plastic concrete. However, considering that high pressures were to be used, it was necessary that the entire system, except for the space occupied by the specimen to be tested, be occupied by water, and all air excluded except that contained within the specimen. A testing machine is used to load a ram, which in turn applies pressure to the water within a container holding the specimen. The water is forced into the concrete, reducing the volume of the air within the specimen, depending upon the amount of pressure exerted. The volume of air is calculated from the drop of the ram by application of Boyle's Law.

DESIGN OF APPARATUS

In the design of the high pressure air meter, several critical phases were considered, the most important of which will be briefly discussed.

An adequate safety factor to assure safety of operation, successful testing, and minimum expansion of the apparatus when subjected to pressure, was considered of utmost importance. Investigation of radial, tangential, and axial unit stresses on the basis of formulas applicable to heavy-wall tubing and guns, and with information available as to bursting strength of mechanical cold drawn seamless steel tubing, the necessary physical size of the equipment for steels of definite properties could be readily obtained.

It was desired that the apparatus should be able to withstand working pressures up to 5000 psi. Since tubing available locally was of uncertain composition, it was believed that a unit stress of 45,000 psi. was the maximum that could be permitted without danger of exceeding the elastic limit. A design for which a maximum pressure of 10,000 psi. would produce this stress would have a safety factor of 2 under the 5000 psi. working pressure. This would not be adequate under all conditions, but since elevated temperatures and shock loads would not have to be provided for, this safety factor was considered reasonable. Having further decided upon the maximum size specimens to be tested (5- by 10-inch cylinder, the standard laboratory specimen nearest in size to drilled pavement cores), the design evolved demanded a length of 6-inch ID by 7½-inch OD (¾-in. wall) seamless tube.

The closure and gasket or sealing surface was also considered of great importance. In order that the choice of gasket material would not be critical, it was believed essential that the gasket be confined in an annular groove or notch to prevent it from blowing out. The lid is of the internal type and is elliptical so that it can be inserted into the specimen chamber by orienting its minor axis in direction of the major axis of the opening, then rotating it and clamping it sufficiently tight under the opening to seal until the pressure is applied. The use of an elliptical lid entailed some difficult machine work, which was finally accomplished in the Illinois Division of Highways' own shop, after several commercial shops had expressed their reluctance to undertake it. The system has worked very well after a good mating surface was achieved between the inside lip of the container and the lip of the closure.

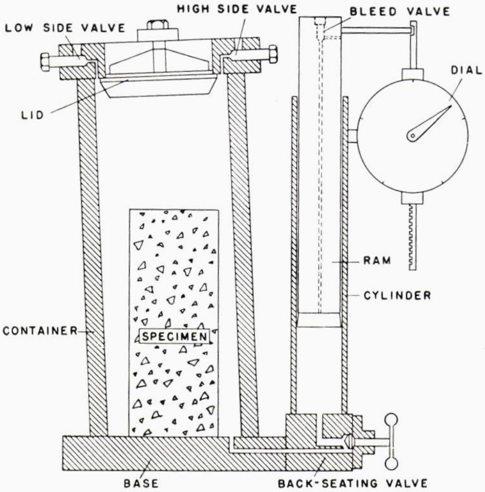

Figure 1. Schematic diagram of high pressure air meter.

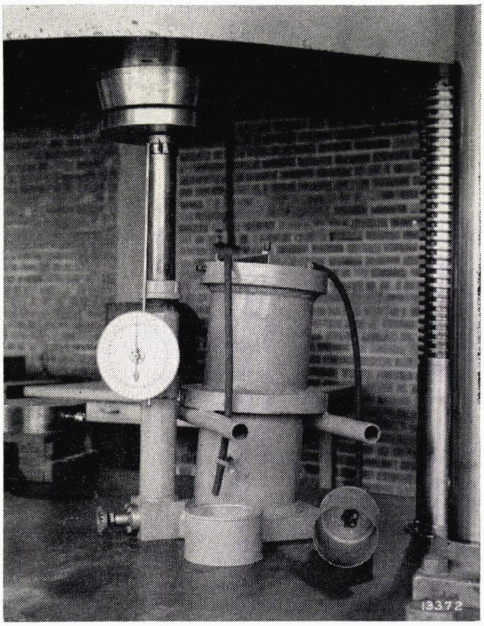

Figure 2. High pressure air meter in testing machine ready for application of pressure.

The connection of a cylinder and ram to the specimen chamber was given major consideration. The cylinder was welded to a specially constructed valve of the brass-stemmed back-seating type, designed to prevent loss of volume through leakage. With the valve block welded to the base of the specimen container, after cross drilling through the base plate, outside connections and tubing were unnecessary and several potential sources of leakage were eliminated. In practice, the valve appears to be unnecessary and is no longer used. The packing around the ram at the top of the cylinder exerts sufficient friction against the ram to maintain it in position so that the water in the cylinder is not forced into the specimen chamber when the closure is removed.

The specimen container was welded to the base plate 6 degrees out of plumb to facilitate the bleeding of entrapped air from the system, which is accomplished by two valves at the top of the container, one at the high and the other at the low side. On the top of the ram is a valve for bleeding entrapped air from the cylinder through a hole drilled the entire length of the ram. The travel of the ram is indicated on a circular scale, graduated in $\frac{1}{64}$-inch intervals, by a pointer actuated by a rack and pinion movement.

Figure 1 is a schematic diagram of the apparatus. Figure 2 shows the high pressure air meter in the testing machine ready for application of pressure. Figure 3 shows the apparatus and its removable parts, the stirrup used for lowering specimens into the container, and the funnel and hose connections used in

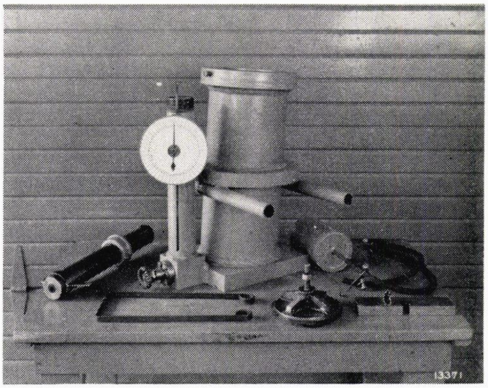

Figure 3. High pressure air meter with removable parts and accessories displayed.

replacing entrapped air in the system with water.

DETERMINATION OF ENTRAINED AIR AND CALIBRATION OF APPARATUS

For the purpose of demonstrating the method of determining the amount of air entrained in a test specimen from the movement of the ram, the following nomenclature was adopted:

B = atmospheric pressure, assumed as 14.4 psi.
P = pressure applied through ram in psi.
V_1 = original volume of air in specimen in cubic inches.
V_2 = volume of air in specimen under pressure P in cubic inches.
V_3 = volume of specimen in cubic inches.
X = movement of ram under pressure P in units of $\frac{1}{64}$ inch.
E = combined expansion of equipment and reduction of volume of water under pressure P expressed in terms of ram movement; that is, in units of $\frac{1}{64}$ inch.
A = cross sectional area of ram cylinder, or 3.1416 square inches.

With a specimen in the container and the apparatus filled with water, all air being evacuated except that entrained in the concrete, the specimen, in addition to atmospheric pressure, is subjected to the pressure exerted by a small head of water and that produced by the weight of the ram, if any. Due to the resistance of hardened saturated concrete to entrance of water under low pressure, the entrained air will be considered to be subjected initially only to the atmospheric pressure B. Under the pressure P exerted through the ram, the entrained air is subjected to the pressure $B + P$. In accordance with Boyle's Law, and assuming that the pressure extends effectively to all the entrained air, there exists the relationship

$$BV_1 = (B + P)V_2 \qquad (1)$$

The part of the ram movement that represents water forced into the specimen obviously is $X - E$, expressed in sixty-fourths of an inch, and since the area of the ram cylinder is A, the volume of water forced into the specimen is

$$\frac{(X - E)A}{64} = V_1 - V_2$$

and

$$V_2 = V_1 - \frac{(X - E)A}{64} \qquad (2)$$

Substituting the value of V_2 from Equation (2) in Equation (1) and solving for V_1,

$$BV_1 = (B + P)V_1 - \frac{(B + P)(X - E)A}{64}$$

$$V_1 = \frac{(B + P)(X - E)A}{64P}$$

or expressed as a percentage of the volume of the specimen V_3,

$$\frac{100V_1}{V_3} = \frac{100(B + P)(X - E)A}{64PV_3} \qquad (3)$$

Substituting the numerical values for B and A, and taking the value of P as 5000 psi., Equation (3) reduces to

$$\text{Entrained air} = \frac{4.923(X - E)}{V_3} \text{ percent} \qquad (4)$$

The effective use of Equation (4), in any given instance, obviously depends upon the successful determination of the quantity E. While data on compressibility of water are available, the problem is complicated by the fact that the expansion of the apparatus is included in this value. Furthermore, the volume of water is not a constant but depends upon the volume of the test specimen. It was considered necessary, therefore, to determine the value E for various amounts of water in the system.

From data on compressibility of various materials, it was determined that the reduction in volume of steel, when subjected to pressures over the range used in the apparatus, was so small in comparison with that of water that it could be disregarded without significant error. For this reason, and since steel does not have internal pore space accessible to water, it was used in calibrating the apparatus for the value of E, the amount of water in the system being varied by inserting varying amounts of steel in the specimen container to simulate the volume of water displaced by specimens of various sizes. In these tests, the stirrup used in lowering a specimen into the container, and removing it after the test, was left in the container during the ap-

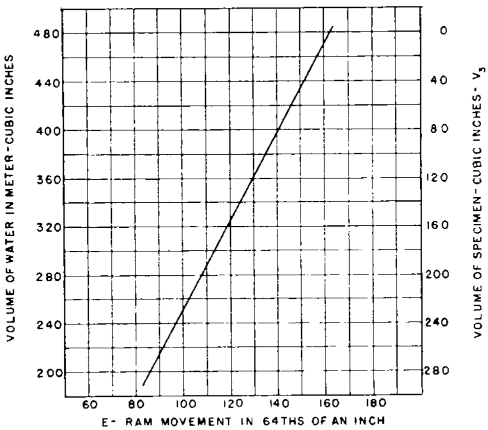

Figure 4. Calibration curve showing the relations between E and amount of water in system and between E and V_3.

plications of pressure, in the same manner as in testing concrete specimens, so that no correction would be necessary for it. The data from these tests, for the pressure of 5000 psi., are shown in the calibration curve in Figure 4, in which E is plotted against the volume of replaced water; that is, the specimen volume V_3.

Concrete specimens, as will be further explained, are prepared for the test by oven drying and subsequent saturation. The amount of absorbed water and the volume of the surface-dried saturated specimens are, therefore, easily determined. The absorbed water should be considered as a part of the water in the system, and V_3 is the volume of the surface-dried saturated specimen. With the volume of the specimen known, the value of E determined from Figure 4, and X being the movement of the ram obtained from the test, the percentage of the entrained air may be calculated from Equation (4).

Since the relationship between E and V_3, demonstrated in Figure 4, without question is linear, and since the part of E that represents expansion of equipment is a constant, the compressibility of the water is represented by the slope of the curve which, with reference to the left-hand vertical scale, has been determined to be approximately 38×10^{-6} cubic inches per cubic inch per atmosphere of pressure, the 5000 psi. representing 347.22 atmospheric pressures of 14.4 psi. This calibration was made at a testing temperature of approximately 80 F. Data available on compressibility of water reveal a corresponding value of 43×10^{-6}, representing atmospheric pressure at sea level and a temperature of 32 F. There is no important difference between the two values, considering that an atmospheric pressure at sea level generally is taken as 14.7 psi. and that the temperature of water apparently influences its compressibility to a small degree. The reduction of the volume of entrained air under the 5000 psi. pressure is very considerable. In fact it is reduced by 99.7 percent of its original volume.

The value of E at the intersection of the curve with the horizontal axis was calculated from the slope and was found to be approximately 31.5. This point represents the condition where all of the water in the system is completely replaced by the specimen, which cannot be attained but which can be approached as a limit. The intercept, therefore, undoubtedly represents the expansion of the apparatus under the pressure, which expressed in volume displacement by the ram is only 1.55 cubic inches. Considering the other limiting condition, that of the system completely filled with water, representing a total volume of 478 cubic inches, reference to Figure 4 shows that the value of E is 160.1, and the part of this due to reduction in volume of the water is $160.1 - 31.5 = 128.6$, which value represents a volume displacement at the ram of about 6.31 cubic inches or about 1.32 percent of the volume of water. It will be noted that for the system completely filled with water, the reduction in the volume of water is about four times as great as the expansion of the apparatus.

DEVELOPMENT OF TESTING PROCEDURE

Before establishing a procedure of testing, considerable preliminary work had to be performed. Tabulated data and a detailed account of the early test results are given in a preliminary paper (*1*). The following is a brief account of the problems involved and the studies conducted.

Since air voids in concrete capable of absorbing water easily cannot be considered entrained air, it seemed obvious that the air content determinations would have to be made on the concrete in fully saturated condition. From observations of the results of permeability tests and determinations of freezable water in concrete, it was anticipated from the beginning that applied pressure might not extend to the minute bubbles of entrained air in concrete specimens that had never been permitted to become dry. Some of the preliminary tests, therefore, involved comparative tests of specimens that had not been removed from the moist room prior to testing and similar specimens that had been oven-dried and resaturated immediately before testing. The results proved definitely that oven drying with subsequent saturation was a necessary element of the test.

Other tests followed to determine the appropriate lengths of the periods of oven drying and saturation. A 72-hour drying period at 280 F to 300 F with a subsequent 48-hour saturation period were finally adopted as being best suitable for concrete of all air contents. Shorter periods can be used, but the applied pressure must be maintained for some time, especially for concrete of the higher air contents. For example, for concrete of 6.1 percent air content, oven-dried for only 24 hours and saturated for 48 hours, it was necessary to maintain the 5000 psi. pressure more than 30 minutes before the external and internal pressures became balanced, as shown by the ram movement indicator.

The effect of size of specimen was studied in comparative tests of 3-by-6-inch, 4-by-8-inch, and 5-by-10-inch cylinders made from the same concrete, and no noteworthy differences were observed in the results obtained. The 5-by-10-inch cylinder, being most nearly of the same size as the 4.5-inch diameter cores drilled from the pavements, was used in most of the earlier tests, but present practice is to use the 4-by-8-inch cylinder because it is easier to insert and remove from the specimen chamber.

The applied pressure was varied from 500 to 5000 psi. The latter value was found to be best suited for the test, since it was found necessary to maintain the lower pressures for undue periods before balance was obtained with the pressure created within the specimens. In some cases, it was observed that it was necessary to maintain even the 5000 psi. pressure over periods varying from 1 to 5 minutes. Pressures in excess of this have not been tried, because it was not desired to overload the apparatus, but a higher test pressure may be advantageous.

It is felt that since the pressure penetrates to the small bubbles of entrained air, it also penetrates to the air voids in the aggregate particles, and corrections are made for this. These corrections are determined from tests in the high pressure meter of aggregates from the same sources as those used in the concrete, in saturated condition, though preliminary oven-drying appears unnecessary.

APPRAISAL OF THE HIGH PRESSURE METHOD

In addition to the development of a suitable method of testing, the preliminary tests involved several additional studies. It was found that the air contents determined on a specimen could be reproduced with good accuracy in successive independent determinations and at different ages of the concrete. The method also was observed to provide excellent differentiation between concretes of different air contents, but yielded in general somewhat higher values than had been observed for the same concrete in plastic state. However, with additional determinations made on concrete of very high air contents, it appeared that, for air contents higher than 6 or 7 percent, the tests of the plastic and the hardened concrete yielded about the same results.

The comparisons made are summarized graphically in Figure 5. It will be seen that a straight line extending from the point representing 7.25 percent of air in both plastic and hardened concrete, and extending to the point representing 0 percent air in the plastic con-

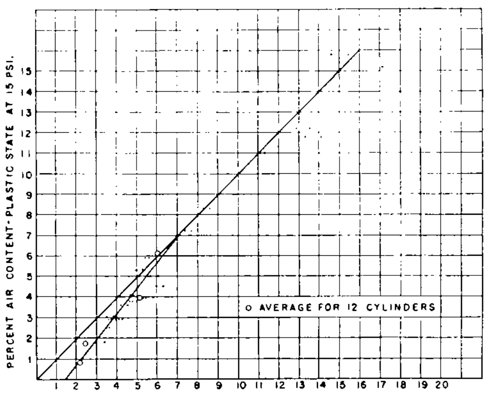

Figure 5. Relationship of air content of hardened concrete to air contents of the same concrete in plastic state.

crete and 1.45 percent air in the hardened concrete, is a fair indication of the relationship existing over the range of air contents usually used, whereas the 45-degree line probably represents the relationship satisfactorily for the higher air contents. Probably the true relationship is a curve deviating but slightly from the indicated straight lines. Air contents determined by the high pressure method are corrected for the indicated discrepancy (See Appendix).

That the discrepancy is not due to a fault inherent in the high pressure apparatus is indicated by the fact that samples of plastic concrete rodded into a suitable container and tested by the high pressure method show air contents practically identical with those determined on the same concrete with the air meter designed for that purpose, utilizing a pressure of 15 psi. The data obtained with respect to this are shown in Figure 6, and are considered as definitely indicating the reliability of the high pressure meter.

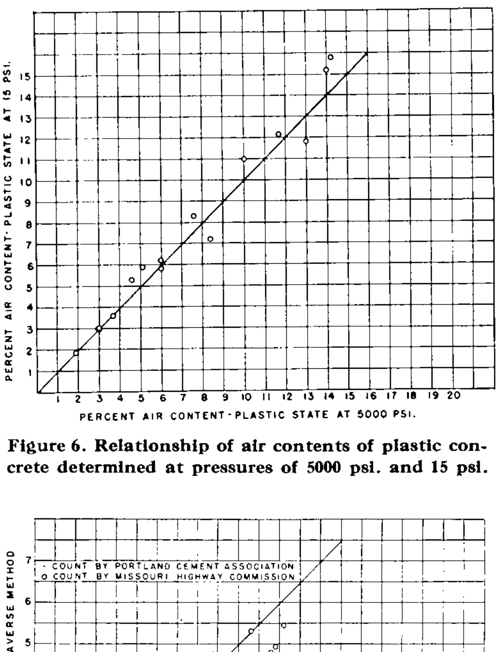

Figure 6. Relationship of air contents of plastic concrete determined at pressures of 5000 psi. and 15 psi.

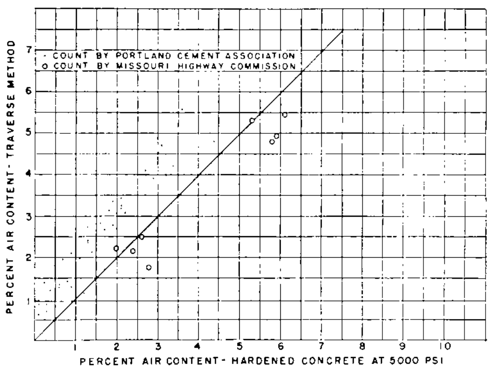

Figure 7. Comparisons of air contents of hardened concrete determined by the high pressure method and by microscopic means.

Some comparisons have been made between air contents determined by the high pressure method and by microscopic means. The remaining pieces of cores, from which a central section had been sawed for microscopic determinations of their air contents by the Portland Cement Association, were tested in the high pressure meter. The air contents obtained by the pressure method were somewhat lower than those determined by the microscopic method. A few cylinders, representing both low and high air contents, were tested in the high pressure meter and then sent to the Missouri Highway Commission for tests by microscopic means. The results obtained were fairly comparable, though the pressure method tended to yield somewhat higher values than those obtained by the microscopic method.

The data obtained are compared in Figure 7. The curve drawn represents the line of equal air contents by the two methods. That the Portland Cement Association data fall above the line may be a consequence of the fact that the pieces of concrete tested in the high pressure meter were rather thin. The same tendency was found later in tests of cores split longitudinally, though reducing the size of cylindrical specimens by dividing them transversely did not alter the air contents materially. Also the possibility that the methods used by the Portland Cement Association and the Missouri Highway Commission might result in somewhat different air contents is not excluded. However, excellent parallelism is shown by the two sets of data. It is felt that additional data of this nature are desirable, and steps are being taken to make further comparisons.

Only in some tests of cores drilled from two pavement sections, for which a processed limestone sand was used, did the pressure method indicate undue differences in results from those determined by other methods. The air content of the plastic concrete at the time of construction averaged 4.0 percent on one section and 4.2 percent on the other. Some difficulty was experienced in obtaining the desired air content and the amount of air-entraining solution necessary ranged from two to three times the usual amount. Cores drilled from the pavement showed rather low strengths. Thirteen cores from one section and 20 from the other selected at random, were retained for air content determinations and the values obtained averaged 6.7 and 6.9 percent, respectively. Because of this discrepancy, eight of the cores, selected to represent a large range in air contents, which averaged 6.2 percent, were sent to the Portland Cement Association for determinations by microscopic means. The air contents obtained averaged 4.1 percent in agreement with the results obtained on the concrete in plastic state. Since low strengths, and also low specific gravity of this concrete, could easily be caused by high air contents, it is intended to make further studies in the laboratory of concrete made from the materials used on that project.

The high pressure meter has been used for routine tests of cores drilled from pavements during the last two years. During 1954, the air contents of 610 cores tested averaged 3.7 percent. Air contents determined from 3653 tests of the same concrete in plastic state averaged 4.0 percent. There was considerable difference in the range of the air contents determined. For the hardened concrete, about 1 percent of the tests showed air contents below 1.0 percent and a slightly greater percentage showed air contents above 7 percent. For the plastic concrete, the number of tests showing such large deviations from the desired air content was negligible. The reason for this may be that air contents determined on the plastic concrete during periods of adjustment to determine the correct amount of air-entraining admixture to be used probably are not shown on the reports from the field.

While much is yet to be learned about the high pressure method, it appears at this time that data obtained with it are sufficiently reliable. While the time consumed in making a test is five days, a great number of specimens can be oven-dried and subsequently saturated without much attention. The number of tests made has ranged as high as 65 in one day.

There has been considerable speculation as to the reason why the air contents determined run a little higher than those determined for the same concrete in plastic state, and must be corrected for this deviation. It is felt that the compressibility of the concrete specimen under the 5000-psi. pressure is at least partly responsible for this. An attempt will be made to produce a new calibration curve similar to the one in Figure 4, obtained by placing different volumes of concrete of a known air content in the specimen chamber. The ram movements obtained, when corrected for the compressibility of the entrained air, should then represent the combined expansion of the apparatus and the compressibilities of the water and specimen, which presumably will result in slightly different values for E in Equation (4) for any given specimen volume.

HIGH PRESSURE METER FOR DETERMINING VOIDS IN BITUMINOUS CONCRETE

It is a well known fact that the volume of voids in bituminous concrete cannot be calculated satisfactorily in most instances, because the aggregates generally absorb some asphalt and the correct specific gravities for use in such calculations cannot be readily determined. The use of the air meter designed for plastic concrete for determining the voids was tried some years ago, and seemed to offer some promise in connection with specimens taken from the road after they had aged a little. The 15-psi. pressure, however, failed entirely to penetrate specimens made in the laboratory.

The high pressure meter has been used experimentally in a number of tests for determining the voids in laboratory made specimens of bituminous concrete. The results obtained fall between those determined analytically by using the apparent and the bulk (oven-dry) specific gravities of the materials and, therefore, appear to be about correct. There is no indication that the pressure penetrates to the void space within the aggregate particles which appears to be effectively sealed by the asphalt. A high pressure air meter especially designed for this work is contemplated.

SUMMARY

From the experimental work and routine testing conducted to date, the high pressure air meter appears to be a very useful addition to the equipment now used in the control of the production of concrete. The following points are of specific interest:

1. Oven drying with subsequent saturation

of the concrete is a necessary element of the test. Seventy-two hours of oven drying followed by 48 hours saturation was found best suited for concrete of all air contents. The pressures used were incapable of penetrating concrete that never had been permitted to dry or had been kept wet over an extended period.

2. The size of the specimen did not have any noteworthy effect on the air contents determined, except that thin pieces, such as cores split longitudinally, showed reduced air contents. Reduction in size of cylindrical specimens by sawing them into halves transversely did not change the air contents significantly.

3. The test pressure of 5000 psi. was best suitable for concrete of all air contents. Lower pressures can be used but require more time for penetrating the air voids of the concrete. Higher pressures were not tried.

4. The high pressure method has shown good reproducibility of air contents determined on the same specimens in successive independent tests and at different ages, and excellent differentiation between concretes of different air contents.

5. For air contents within the range usually required, the high pressure meter shows air contents a little higher than those obtained on the same concrete in plastic state. It is felt that the compressibility of the specimens under the high pressure, which would appear as an increased air content, is at least in part responsible for this. The air contents determined must be corrected for this deviation.

6. The air contents of plastic concrete determined with the high pressure meter are in excellent agreement with air contents determined on the same concrete with the air meter designed for this purpose, utilizing a pressure of 15 psi. This is taken as indicating the general accuracy of the high pressure method.

7. Comparison of the high pressure method with determinations by microscopic means has shown reasonable agreement of air contents for cylindrical specimens.

8. Except for some apparently too high air contents obtained on some concrete made with a processed limestone sand, the high pressure meter has shown excellent results in routine air content determinations of drilled pavement cores.

9. While five days are required for testing an individual specimen, a large number of specimens can be handled at the same time. The number of tests made has ranged as high as 65 in one day.

10. The high pressure method shows excellent promise as being suitable for determining the voids in specimens of bituminous concrete.

ACKNOWLEDGMENTS

The high pressure air meter was developed in the mixtures control section of the Bureau of Materials under the direct supervision of O. Larsen, Mixtures Control Engineer. F. H. Blandin, Concrete Control Engineer, and J. H. Aschauer, Equipment Design Engineer, performed the pioneering work with respect to the method and developed the design of the apparatus. Credit is due to G. E. Koerner, Instrument Designer, for performing some difficult machine work.

REFERENCE

1. Blandin, F. H., and Aschauer, J. H., "High Pressure Meter for Determining Air Contents of Hardened Concrete," *Illinois Highway Engineer*, Vol. V, No. 3, 1953.

APPENDIX

Equation (4) has been further developed to yield the air contents of the concrete specimens automatically corrected for the air contained within the aggregate particles and the deviation in air content of the hardened concrete from that of the same concrete in plastic state. It is expedient to introduce the following additional nomenclature:

a = percentage of air within the aggregate particles based on the specimen volume V_3.

Y = the part of the ram movement due to the air held within the aggregate particles.

E' = E in Equation (4) increased by the part of the ram movement which is due to air held within the aggregate particles, or $E + Y$.

H = percentage of air in the hardened concrete as determined from Equation (4).

P = percentage of air in the same concrete in plastic state.

Referring to the discussion of the chart in Figure 4, it will be recalled that the intercept of the calibration curve with the horizontal axis was determined to be at 31.5, representing ram movement due to expansion of the apparatus, and that the ram movement with the entire system filled with water is 160.1, both of these values being in units of $\frac{1}{64}$ inch. Further, the volume of the system is 478 cubic inches. It is apparent therefore that the reciprocal of the slope of the line is

$$\frac{160.1 - 31.5}{478} = 0.269$$

Bearing in mind that the water absorbed by the specimen is a part of the water of the system, and assuming that the water absorbed is $\frac{1}{10}$ of the volume of the test specimen, this being approximately correct for the type of concrete usually tested, there remains a volume of $0.9V_3$ representing concrete and entrained air. It is apparent, therefore, that the equation of the calibration curve in Figure 4, in terms of slope and intercept on the horizontal axis, with satisfactory approximation, is

$$\begin{aligned} E &= 31.5 + 0.269\ (478 - 0.9V_3) \\ &= 160.1 - 0.242V_3 \end{aligned} \qquad (5)$$

In accordance with the adopted nomenclature, the original volume of air within the aggregate particles is

$$\frac{aV_3}{100}$$

It was also brought out in the discussion that the volume of air under the pressure is reduced by 99.7 percent. The volume reduction of the air within the aggregate particles, therefore, is 0.997 of its original volume, which is translated into inches of ram movement, by dividing by the area of the ram, and into units of $\frac{1}{64}$ inch by multiplying by 64. The part of the value E, therefore, which is due to the air within the aggregate particles is

$$Y = \frac{64 \times 0.997aV_3}{3.1416 \times 100} = 0.203aV_3 \qquad (6)$$

This added to the value of E in Equation (5) results in the expression

$$E = 160.1 - 0.242V_3 + 0.203aV_3 \qquad (7)$$

which value, when used in Equation (4) instead of E, corrects the total ram movement X for the part of the movement that is due to expansion of the equipment and the compressibilities of the water and the air entrained within the aggregate particles.

Referring also to the discussion with respect to the chart in Figure 5, it will be recalled that the relationship between the air content of the hardened concrete, as determined by Equation (4), and that of the same concrete in plastic state, for air contents within the range ordinarily encountered, is depicted by the straight line having the intercept of 1.45 on the horizontal axis and extending to the point representing 7.25 on both coordinate axes, each expressed in percent. The reciprocal of its slope is

$$\frac{7.25 - 1.45}{7.25} = 0.8$$

and the equation of the line in terms of slope and intercept with the horizontal axis is

$$H = 1.45 + 0.8\ P$$

or

$$P = 1.25H - 1.812 \qquad (8)$$

which expresses the air content of the plastic concrete in terms of the air content determined on the same concrete in hardened state, for any value of H less than 7.25 percent. The value H is expressed by Equation (4). Substituting in it instead of E the value of E' from Equation (7), and further substituting the resulting value of H in Equation (8),

$$P = 1.25 \left[\frac{4.923(X - 160.1 + 0.242V_3 - 0.203aV_3)}{V_3}\right] - 1.812$$

which reduces to

$$P = \frac{6.154(X - 160.1)}{V_3} - 0.323 - 1.25a \qquad (9)$$

Figure 8 is a reproduction of the chart in Figure 5 with all air contents below 7.25 percent representing hardened concrete determined in accordance with Equation (9), and it

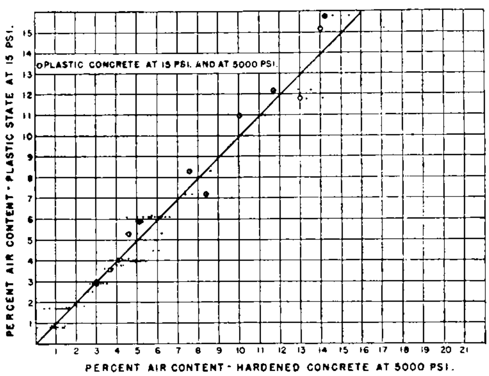

Figure 8. Reproduction of figure 5 with the air contents of hardened concrete corrected by equation (9).

is seen that the points group reasonably along the line denoting equal air contents for plastic and hardened concrete. In practice, a set of charts is used, in which $X - Y$, the total ram movement diminished by the part of this movement due to air within the aggregate particles as given by Equation (6), is plotted against P, the percentage of air determined from Equation (9), for various values of the specimen volume V_3.

DISCUSSION

THOMAS B. KENNEDY, *Chief, Concrete Division, Waterways Experiment Station, Jackson, Mississippi*—The Illinois Division of Highways is to be congratulated for successfully building and operating the high-pressure apparatus for determining air content of hardened concrete described in Mr. Lindsay's article. We intend to make and use such a machine.

Work done at the Concrete Division of the Waterways Experiment Station several years ago parallels somewhat the efforts of the Illinois Division of Highways. The article by Vellines and Ason (*1*) suggested to us that the air content of hardened concrete could be obtained by use of some sort of pressure apparatus.

We built two machines, one for test of 10 x 20-inch cylinders and the other for test of 3½- x 4½- x 16-inch beams. The machines appeared to work and the results of our experiments were given in a short report at the Research Session of the ACI Convention in February 1951, in San Francisco. An account of this work was subsequently published in "Concrete" (*2*). The article in "Concrete" treats of more than one subject, but the last third of it deals with determining air content of hardened concrete by pressure.

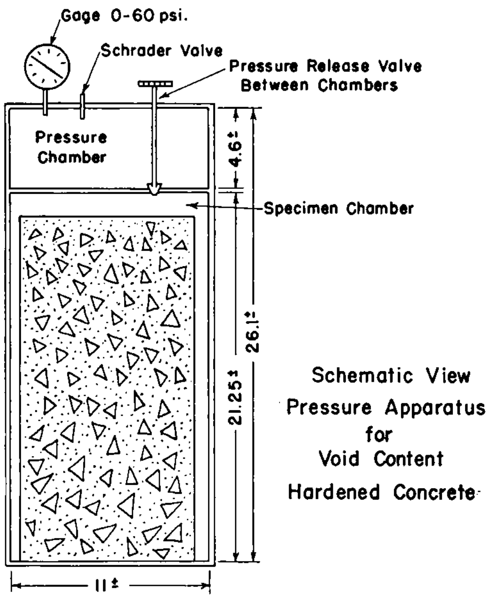

Figure 1. Schematic view: pressure apparatus for void content hardened concrete.

The apparatus consisted of two interconnected calibrated chambers. One chamber contained the specimen whose air content was to be determined and the other contained air compressed to 30 psi. When the valve between the two chambers was opened, the system came to equilibrium. The reading on the gage was a function of the volume of the system available to be filled by air, which was influenced by the volume of the specimen. Figure 1 is a schematic drawing of the apparatus. The void content of the specimen was simply the difference between the apparent volume of the specimen from physical measurements, and its absolute volume calculated from the equilibrium pressure by the following formula:

Percent Air =

$$P_1V_1 - P_2(V_1 + V_2 - V_3)\ 100\ P_2V_2$$

where: P_1 = Initial pressure in chamber.
P_2 = Equilibrium pressure on the system.
V_1 = Volume of pressure chamber.
V_2 = Volume of specimen chamber.
V_3 = Volume of the specimen including voids.

We tested several concretes on removal from moist (fog room) curing, after 28 days drying in laboratory air, after drying at 100°C for 7 days, and after soaking in water for 96 hours following the 7-day drying. Values agreed reasonably well with those calculated from the mixture proportions and as indicated by tests on the freshly mixed concrete. Our main difficulty stemmed from the fact that we were using low air pressure (30 psi) to effect our tests and the time required for the system to come to equilibrium not infrequently was 48 hours and in one case, was 116 hours.

The extremely long time occasionally required to reach equilibrium removed the test from the realm of the practical and discouraged us somewhat. Personnel restrictions prevented us from experimenting along the lines reported in this paper, although such a course was discussed.

REFERENCES

1. Vellines, R. P., and Ason, T., "A Method for Determining the Air Content of Fresh and Hardened Concrete," ACI Proceedings, Vol. 45, p. 665.
2. Kennedy, T. B., "Investigation of Methods to Determine Air Content of Mass Concrete," *Concrete,* December 1952, pp. 18 and 20.

J. D. Lindsay, *Closure*—The interest shown by Mr. Kennedy and others in the high pressure method of determining air contents of hardened concrete is highly gratifying. As the method is studied and used by others, it may be expected that the problems that now appear enigmatic will gradually be cleared up. In the meantime, the successful use of the method must depend on a calibration of the apparatus by testing in it concerete specimens of known air contents.

During the discussion following the presentation of the paper, a question was raised as to whether discrepancies in the air contents determined could be due to failure of fully saturated specimens, during the period of resaturation, to absorb the same amount of water as was lost during the oven drying. The early tests indicated that essentially the same amount of water was absorbed, and recent tests have confirmed that this is the case for the average of the specimens, and that errors from this source seldom would be as much as ½ percent in the air contents determined. Furthermore, a correction can be made for this, if desired. Another question raised was whether the specimens after the tests could be satisfactorily used for compressive strength determinations. This has not been given any recent study but, based on tests conducted some years ago, the specimens would show much too low compressive strengths, at least without further prolonged curing.

It was mentioned in the paper that discrepancies between the air contents determined on plastic and hardened concrete were thought to be in some manner connected with the compressibility of the concrete under the high pressure, and that an attempt would be made to recalibrate the apparatus for the value E, using concrete specimens of known air contents instead of the steel cylinders used in the original calibration. A few of these tests have been made and the data for one high and one low air content, completed to date, produced definite, almost linear plots. An explanation on the basis of compressibility of the concrete, however, does not at this time appear tenable. It is possible that strain measurements of the concrete would aid in the study of the effect upon the specimens of the high external and internal pressure produced in the test.

Since the presentation of the paper, a high-pressure air meter designed especially for determining air voids in bituminous concrete specimens has been constructed and is being used experimentally. This meter is also designed for a maximum pressure of 5,000 psi, is hand-powered and therefore portable, and it is felt that several improvements have been incorporated in it.