Preliminary Tests of a New Surface Airflow Device for Rapid In Situ Indication of Concrete Permeability

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The development of a prototype surface airflow device for concrete is described. The method is based on measurement of the rate of airflow through a vacuum plate placed on a concrete surface under a vacuum of approximately 25 in. of Hg. Effective depth of measurement is demonstrated to be approximately 0.5 in. below the surface. For calibration of the method, concretes were cast using a variety of water-to-cement ratios as well as admixtures such as latex and silica fume. Results were found to correlate well with chloride diffusion constants derived from 90-day ponding tests, as well as with true air permeabilities measured using a pulse decay technique. Design of a field prototype based on the surface airflow technique is also presented. The field instrument is designed to obtain readings at the rate of approximately one per minute, and be powered by rechargeable battery packs. Although surface moisture has an influence on test results, simple techniques for rapid drying of small test areas have been developed. Plans for future testing are presented.

There is a growing awareness of the important role of permeability with regard to the long-term durability of concrete structures. Much of this interest relates to the realization that durability may be directly related to permeability of the concrete in question. If an aggressive substance, be it water, sulfate or chloride ions, or other materials, can be kept out of concrete by virtue of low permeability, then associated problems, such as freeze-thaw deterioration, corrosion of reinforcement, and formation of expansive components, may be mitigated. Therefore, there has been an interest not only in determining permeabilities of conventional concretes but also in developing improved concretes having low permeabilities.

The need for data on concrete permeability dates from the early 1930s, when designers of large hydroelectric structures required information on rates of passage of water through concrete under the influence of relatively high hydraulic heads. In such instances, flow of water through concrete can be adequately described by Darcy's law (*1*),

$$Q = \frac{KA}{\mu} \cdot \frac{dp}{ds} \tag{1}$$

where

Q = volume outflow (cm^3/sec),
A = area (cm^2),
μ = viscosity (centipoise),
dp/ds = pressure gradient (atmospheres per centimeter), and
K = permeability constant (Darcy).

Permeabilities to such fluids as air (*2*), liquid nitrogen (*3*), methane (*4*) and oil (*5*) have also been measured. In general, permeabilities to gases are from one to two orders of magnitude greater than those for water.

Under conditions other than those of saturated fluid flow, transport of substances through concrete can occur by a variety of different mechanisms. These may include (a) capillary attraction, (b) vapor transmission, or (c) ionic diffusion. Data developed by Wing (*6*) and Dunagan (*7*) indicate that movement of water into dry concrete by capillary attraction can be rapid. An initial surface absorption test (ISAT) (*8*) has been developed using these principles.

There is currently much concern with corrosion of reinforcing steel promoted by chloride ions that penetrate through the concrete cover and eventually reach the reinforcement. It is generally believed that such migration of chloride ions occurs primarily through diffusion processes. Various studies (*9,10*) indicate that the coefficient of diffusion is of the order of 10^{-7} to 10^{-8} cm^2/sec. Diffusion will generally follow Fick's second law,

$$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial x^2} \tag{2}$$

where

C = concentration at distance x (cm) from a boundary,
t = time (sec), and
D = effective diffusion coefficient (cm^2/sec).

Improved laboratory techniques that can rapidly assess the permeability of concrete to water, gases, ions, or other substances have been developed. These include techniques based on high pressures (*11*), transient gas flow (*12*), or ionic conductance (*13*). Although these methods offer an improvement in testing speed over previous steady-state techniques, these still require somewhat time-consuming specimen preparation, and the necessity to remove a core from the structure makes testing a destructive process.

Recent emphasis has been on nondestructive field tests that can rapidly assess the permeability of in-place concrete. A review carried out for the Strategic Highway Research Program in 1988 (Whiting, unpublished report) indicated that

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about 20 such tests had been developed, (some only slight variants of others). The most widely used tests included the ISAT (*8*) and the vacuum decay and capillary flow tests devised by Figg (*14*). Most of these tests involved either drilling a small hole into the concrete in which the measurement is carried out, or affixing a test apparatus to the surface of the concrete using clamps or a catalyzed resin seal. An exception was the vacuum decline test developed by Schonlin and Hilsdorf (*15*), which used a vacuum seal on the concrete surface.

In spite of existing tests, a rapid, practical permeability test was needed that provided large numbers of readings on site for given concrete structures in reasonable periods of time. The development of such a test is described in the following sections.

OBJECTIVES AND SCOPE

The objective of the project was to develop a rapid field test for concrete permeability that would correlate reasonably well with existing laboratory techniques. It was recognized that any rapid, nondestructive field test would most likely not yield a true permeability (or diffusion) value but would afford an empirical result that could be taken as a *measure* of relative permeability. Such a device would, ideally, be rugged, portable, battery powered, and simple to operate. The intent was to develop a laboratory prototype first, ensure that results correlated with laboratory techniques, and then construct a workable field instrument. The influences of external variables (such as moisture content, temperature, and surface finish) were also to be investigated.

DEVELOPMENT OF THE METHOD

Basis of the Technique

The surface air flow (SAF) technique is based on the rate of air flow through a concrete surface, more permeable concretes being characterized by higher air flow rates. Rather than force air into the concrete, a procedure that would require a direct pressure seal to be created at the surface, this technique relies on creation of a vacuum at the surface, which causes air to flow out of the concrete along the pressure gradient created by a vacuum pump. The SAF technique is similar in principle to that developed by Schonlin (*15*); however, Schonlin used decay of vacuum as a measure of permeability, and therefore test times were lengthy for low-permeability concretes. The SAF technique affords a more rapid measurement once the desired pressure differential has been achieved.

The SAF technique is designed to give an indication of permeability for a wide variety of concrete materials. These include not only low-permeability concretes, such as those produced using silica fume or polymer modifiers, but also high-permeability concretes created by use of high water-to-cement ratios or poor curing practices. The effective test area is chosen as a circle 2¾ in. in diameter, offering a representative test on a small area of most structural concretes. As the test was designed to be rapid, a practical goal was to be able to obtain readings at 4-ft centers over one lane of a typical bridge deck within a normal working day. The test was to be applicable to support and substructural elements as well, necessitating that the device also be operable in vertical and overhead nodes.

Laboratory Bench Prototype

A schematic diagram of the laboratory bench prototype is shown in Figure 1. The steel vacuum plate of 4-in. diameter is fitted with a ⅛-in.-thick soft rubber ring, allowing for a circular flow area of 2¾ in. in diameter. Flow is initially directed through Valve A until the system reaches the operating pressure of 120 to 140 mm of Hg as measured on the U-tube Hg manometer. Valve A is then closed and the air stream directed through Valve B from the rotameter, which is calibrated to read in units of milliliters per minute over a range of 0 to 280 ml/min. The total test time is approximately 1 min, after which the pump is turned off and air is allowed to reenter the system through Valve C.

Preparation of Test Specimens

After initial system checkouts were complete, a series of concrete test specimens offering a range of permeabilities was designed and constructed. Concrete mixtures are presented in Table 1. The forms were designed to contain (a) rebar mats at ½ and 1½ in. to evaluate effects of reinforcing steel on permeability techniques, (b) brass tubes (5/32-in. diameter) at ¼, ½, and 1 in. from the surface to be used to measure extent of depth of influence of vacuum, and (c) thermocouples at ¼, ½, 1, and 2 in. for temperature studies.

Slabs from Mixtures A through D were cured under wet burlap and polyethylene overnight, then transferred to heavy plastic bags for 28 days of curing. They were then coated on four sides with epoxy and placed in the following environments:

- Continuous air drying at 73 ± 3°F and 50 ± 5 percent relative humidity (air-dry series), and
- Cycling of 1 day wet at 75°F to 80°F and 6 days dry in the same environment (moist series).

Mix E was moist-cured for 28 days to develop a high level of impermeability, then exposed to air-drying. Mix F was exposed to air-drying immediately after demolding, to develop maximum curing of the latex admixture.

PRELIMINARY TESTING

Air-Dried Test Series

The first series of tests was performed on those slabs that had been placed in an air-drying environment for approximately 3 months. A series of 15 individual flow readings was obtained across the cast and finished faces of each slab.

A summary of test statistics is presented in Table 2. Lowest readings were obtained for the silica fume concrete (E), highest for the concrete with $w/c = 0.6$ (D). Readings for latex concrete (F) were somewhat higher than for silica fume, as would be expected. Conventional concretes exhibited an in-

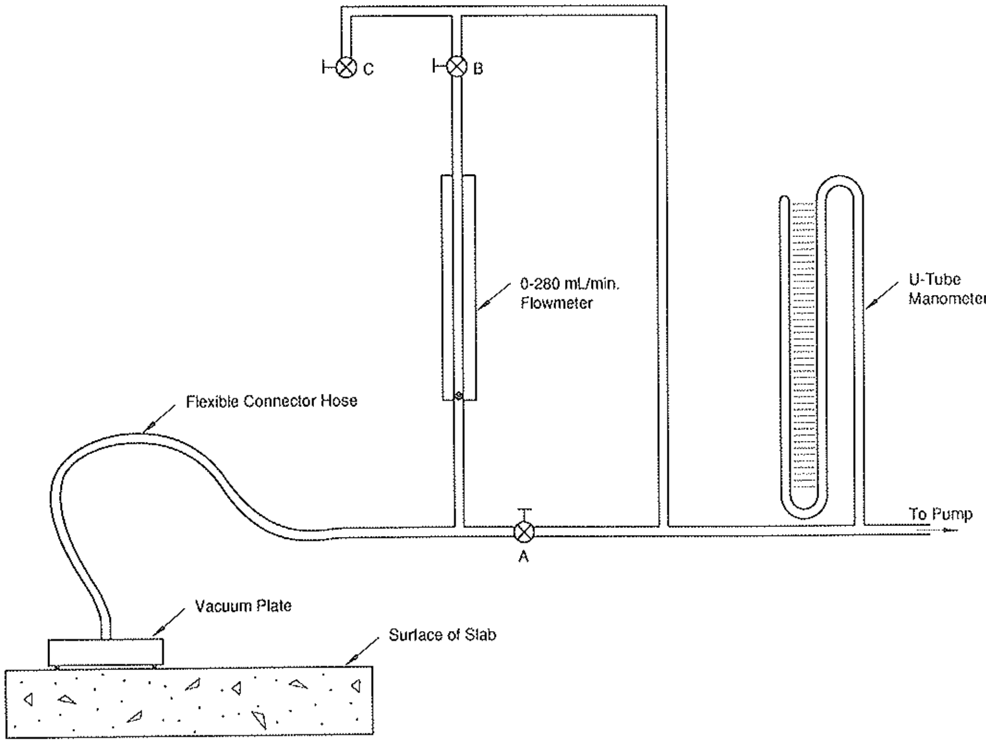

FIGURE 1 Schematic drawing of the laboratory surface airflow device.

creasing air flow with increase in *w/c*, at least on the finished face. There was little difference in air flow between concretes A, B, and C on the cast face, perhaps representing an increased densification at the bottom of the slabs, or some absorption of the mix water by the formwork. On the finished face of Slab C–1, it was not possible to achieve satisfactory readings. Most readings were off scale (i.e., >280 ml/min), and those that fell on scale were unstable. Because this effect might have been caused by leakage around the gasket, a silicone vacuum grease was applied to the gasket and some readings were repeated. This procedure stabilized some readings but most were still off scale. On inspection of the surface that had been coated with grease, a fine network of surface microcracks in the thin surface paste layer was visible. It is likely that this microcracking led to leakage under the gasket and high measured air flows. This surface was then given a light sandblast to remove the surface paste. However, repeat testing still indicated microcracks, which were now even more visible on the newly created surface. This slab may have been prematurely finished or may have suffered from some plastic shrinkage cracking.

The statistics presented in Table 2 were obtained from readings taken at 15 different locations on each slab. Therefore, the variance estimates represent a combination of variability in concrete properties from point to point on the surface as well as inherent test variability. Variability is greater for the finished surfaces, perhaps reflecting differences across the slab caused by hand finishing. In order to obtain a better

TABLE 1 CONCRETE TEST MIXTURES

	Quantities - lb/cu yd							
Mix	Cement	Sand	Gravel	Water	Water/ Cement Ratio	Admixtures[a/]	Slump (in.)	Air (%)
A	659	1263	1772	252	0.38	--	2.6	5.0
B	550	1375	1776	237	0.43	--	3.2	5.3
C	453	1477	1760	227	0.50	--	3.0	5.8
D	374	1563	1720	224	0.60	--	3.8	6.4
E	665	1300	1680	239	0.36	Silica Fume- 67 lb.	5.0	5.0
F	685	1579	1311	185	0.27	Latex 25 gal.	6.9	5.6

a/ Other than air-entraining agents.

TABLE 2 SURFACE AIRFLOW MEASURED ON AIR-DRIED SLABS

Slab	Readings	Face	Air Flow (mL/min) Mean	Minimum	Maximum	Std. Dev.	% C.V.
A-1	15	Cast	67	55	85	8.38	12.5
A-1	15	Finished	50	40	65	6.97	13.7
B-1	15	Cast	68	55	90	8.80	12.9
B-1	14	Finished	87	60	155	26.29	30.2
C-1	15	Cast	64	50	95	11.01	17.3
C-1	a/	Finished	-	--	--	..	--
D-1	15	Cast	152	125	175	13.66	8.9
D-1	15	Finished	128	85	175	29.56	23.1
E-1	15	Cast	19	14	22	2.23	11.7
E-1	10	Finished	16	12	23	3.14	19.4
F-1	15	Cast	22	17	30	3.54	15.8
F-1	10	Finished	34	22	65	12.54	36.9

a/not tested due to surface crazing.

estimate of test reproducibility, a series of measurements was performed consisting of five replicates on each of three positions on cast and finished surfaces of each slab. Summary statistics are presented in Table 3 for the cast faces. The variability of successive measurements at one position is much less than the variability across the slab. This difference indicates that the method was actually detecting differences in permeability across the surface of the slab, most likely caused by small differences in consolidation and finishing across the surface. Reproducibility statistics are not presented for Slab F–1 (latex concrete) because each reading appeared to be successively lower, indicating that air was being evacuated faster than it was being replaced in the time interval between each measurement.

The slabs cast with embedded brass tubes were used to measure the effective depth of penetration of the vacuum into the slabs. During casting, a solid brass rod was extended through the tube. When it was removed, a 1-in.-long cavity was created at the ½ and 1-in. depths. A microflowmeter and a manometer were attached to each well to measure air flow and vacuum level at each depth (Table 4). Results indicate that for low-*w/c* concrete (Slab A–2) only small flow rates could be measured, even at ¼ in. below the surface. For slightly higher *w/c* ratio (Slab B–2), flow at ¼ in. below the surface was approximately 20 percent of the surface reading. For concretes with high *w/c* ratio, flow was much greater at ¼ and ½ in., and was even detectable at 1 in. below the surface. Effects of steel placement and cover on air-flow permeability readings were also investigated. Readings were taken directly above and between No. 5 bars having ½ and 1½ in. of cover. Results are presented in Table 5. There is little significant difference between readings taken above or between reinforcing bars, indicating that reinforcing steel (and presumably other embedments) has little effect on the test, provided cover depth is ½ in. or greater.

Effects of Moisture Content

Testing was performed on slabs that had been subjected to a weekly wetting cycle (1 day soak and 6 days air-dry) since an age of 28 days. The top (finished) surface of each slab was subjected to the soaking. The bottom (cast surface) was protected from direct wetting during the soak but was in a damp environment. Tests were performed on both cast and finished surfaces approximately 1 hr after removal of soaking blankets.

Test results are presented in Table 6. For the finished surfaces, lower readings were encountered for the wetted slabs, the differences between mean dry and wet readings ranging from about 15 units for Batch A to 30 units for Batch D.

TABLE 3 REPRODUCIBILITY MEASUREMENTS

Slab	Face	Position	Air Flow (mL/min) Mean	St. Dev.	% C.V.
A-1	Cast	1	52	2.09	4.0
		6	75	2.74	3.6
		15	54	2.19	4.1
B-1	Cast	1	58	2.50	4.3
		5	68	2.73	4.0
		11	50	2.74	5.4
C-1	Cast	1	50	3.06	6.1
		7	53	2.33	6.1
		15	89	2.24	2.5
D-1	Cast	6	121	6.52	5.4
		7	153	2.50	1.6
		11	161	4.54	2.8
E-1	Cast	1	16	1.79	11.0
		6	21	1.12	5.5
		11	23	1.04	4.5

TABLE 4 EFFECTIVE DEPTH OF VACUUM PENETRATION

Slab	Well Depth (inches)	Air Flow (mL/min)	Vacuum
A-2	Surface	40	-635 mm
	1/4	1.0	nd
	1/2	0.5	nd
	1	0	nd
B-2	Surface	65	-635 mm
	1/4	12.6	-180 mm
	1/2	2.1	nd
	1	0	nd
D-2	Surface	130	-635 mm
	1/4	100	-600 mm
	1/2	13.5	-160 mm
	1	0.4	nd

nd/ no vacuum detected

TABLE 6 COMPARISON OF SURFACE AIRFLOW TESTS ON DRY AND WET SLABS

Batch	Slab	Face	Condition[a/]	Air Flow (mL/min) Mean	Minimum	Maximum
A	A-1	Cast	Dry	67	55	85
		Finished	Dry	50	40	65
	A-4	Cast	Damp	60	45	70
		Finished	Wet	45	25	75
B	B-1	Cast	Dry	68	55	90
		Finished	Dry	87	60	155
	B-4	Cast	Damp	65	48	95
		Finished	Wet	60	40	80
C	C-1	Cast	Dry	64	50	95
	C-4	Cast	Damp	71	55	115
D	D-1	Cast	Dry	152	125	175
		Finished	Dry	128	85	175
	D-4	Cast	Damp	154	85	215
		Finished	Wet	96	65	155
E	E-1	Cast	Dry	19	14	22
	E-2	Cast	Damp	22	15	27
F	F-1	Cast	Dry	22	17	30
	F-2	Cast	Damp	18	9	32

a/ Slabs surface-dry at start of test.

Differences for cast surfaces were less, as the cast surfaces were not directly exposed to liquid water. In order to examine the effects of wetting on cast surfaces, the cast surfaces were placed upright, put through three weekly cycles of wetting, then retested. As with the finished surfaces, there were considerable differences caused by wetting of the test surfaces. These differences were greatest for the high-*w/c* concrete (D–4), and were insignificant for low-permeability concretes (E–2 and F–2). A summary of airflow measurements on the various sets of test slabs under differing conditions of moisture is shown in Figure 2. In spite of the differences induced by varying surface conditions and moisture levels, a general trend of increasing airflow with decreasing quality of concrete is noted. The concretes designed to have low permeabilities (Batches E and F, silica fume and latex concretes) have the lowest airflows. Conventional concretes typical of those specified for structural and paving applications (Batches A, B, and C) reveal a slight upward trend for airflow as *w/c* ratio is increased going from Batches A to C. The poorest-quality concrete produced in this test series (Batch D), exhibits the highest airflow readings.

A preliminary classification of permeability based on airflow measurements is suggested by Figure 2. Readings less than 30 ml/min are generally associated with low-permeability concretes. Readings between 30 and 80 ml/min are associated with moderately permeable concrete (*w/c* from about 0.4 to 0.5). Readings above 80 ml/min are associated with high-permeability concretes. Readings in borderline regions may be ambiguous; for instance, very wet, high-*w/c* concretes may on occasion yield readings close to the moderate zone.

In an attempt to devise a practical means of reducing the effect of near surface moisture content on test results, various drying stategies were carried out. A 12- × 12- × 4-in. louvered sheet metal box was mounted on a slab so that an embedded thermocouple tree (of ¼-, ½-, 1-, and 2-in. thermocouple depths) was at the approximate center of the area. A heat gun of 1,500-watt capacity was then placed in a tube mounted on the top center of the box and activated. Temperature profiles for Slab D–2 (*w/c* = 0.6) are shown in Figure 3. Although surface temperatures reach nearly 300°F, temperatures at ¼, ½, and 1 in. peak at approximately 140°F, 110°F, and 95°F after 5 min of heating. The slab was then allowed to cool for an additional 10 min until all temperatures fell below 90°F. At this time, airflow tests were repeated. Results presented in Table 7 indicate that the surface heating was able to restore flow values close to those obtained on initially dry surfaces. This approach, at least in principle, could offset the interference that moisture appears to have on the test. The 1,500-watt heat gun requires a high energy expenditure, and would necessitate that a relatively large generator be transported to the test site. It was decided to investigate the use of a small hand-held infrared heater fired

TABLE 5 EFFECTS OF STEEL PLACEMENT AND CLEAR COVER

Slab	1/2 Inch Cover above bars	1/2 Inch Cover between bars	1-1/2 Inch Cover above bars	1-1/2 Inch Cover between bars
A-2	50	50	40	40
B-2	ns	ns	60	65
D-2	155	145	135	130

ns/ no stable readings obtainable (crack in concrete above bar).

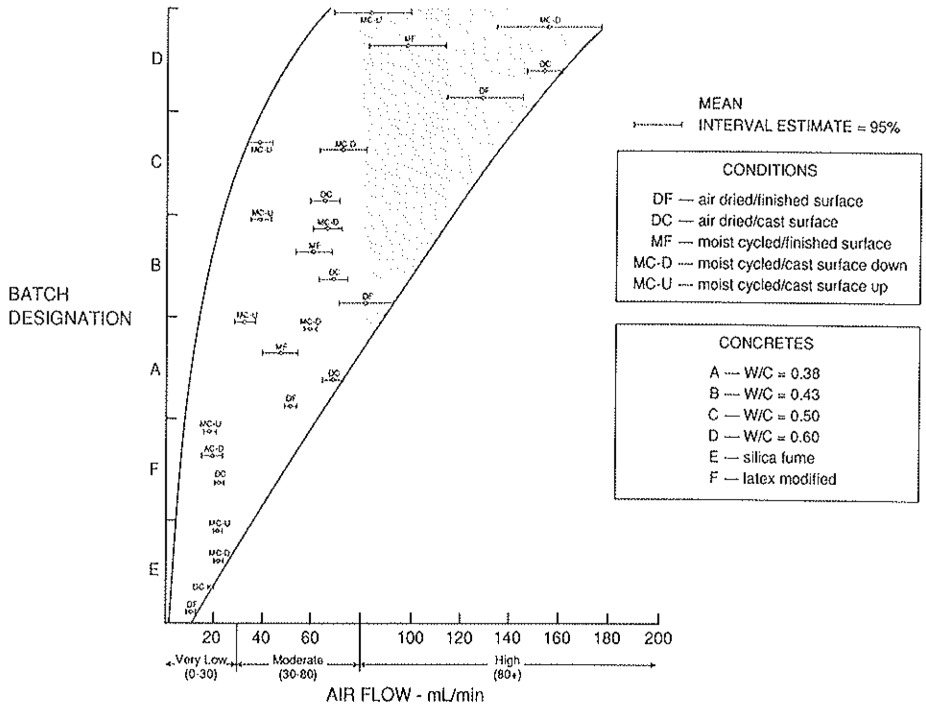

FIGURE 2 Summary of surface airflow measurements.

by liquid propane (such as is used for stripping paint). The heater was held at a height of 4 in. above the desired test areas for periods of 5 min. Heating profiles are shown in Figure 3. Results compared favorably with those for the 1,500-watt heat gun previously tested. After cooling, SAF measurements were made on the heated areas. Results presented in Table 8 indicate that the infrared method is capable of restoring the test area essentially to the initial air-dry condition.

Examination of Figure 3 indicates that essentially the same temperatures at any given depth are reached after 3 min using the infrared heater, as opposed to 5 min using the heat gun. In order to investigate the possibility of using shorter heating times, the slabs were resaturated and the tests carried out using 3 min of heating with the infrared heater. Results presented in Table 9 were again favorable, indicating that a 3-min heating time could be used. Because further tests at

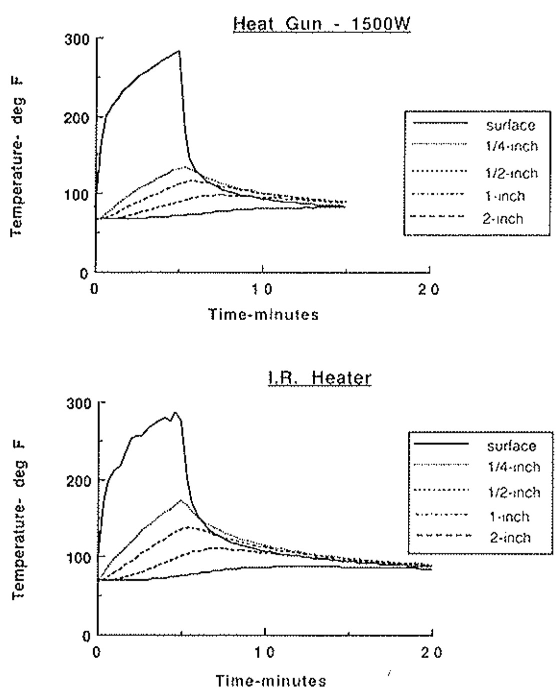

FIGURE 3 Comparison of temperature profiles generated using infrared heater and 1,500-watt heat gun.

TABLE 7 EFFECTS OF SURFACE DRYING USING 1,500-WATT HEAT GUN

Slab	w/c	Initial Flow Air Dry a/ (mL/min)	Flow After Soaking b/ (mL/min)	Flow After Heat Drying c/ (mL/min)
A-2	0.38	45/50	30/35	40/45
B-2	0.43	60/70	45/50	65/70
D-2	0.60	130/140	95/105	125/135

a/ Stored in air at 73±3°F and 50±5% RH for 10 months after curing.
b/ Soaked once weekly for 7 weeks, then continuously for 3 days.
c/ Dried 5 minutes using 1500 W heat gun at 4 inches above surface.

TABLE 8 EFFECTS OF SURFACE DRYING USING INFRARED HEATER—5-min HEATING

Slab	w/c	Initial Flow Air Dry a/ (mL/min)	Flow After Soaking b/ (mL/min)	Flow After Heat Drying c/ (mL/min)
A-2	0.38	45/50	30/35	40/50
B-2	0.43	60/70	45/50	65/70
D-2	0.60	130/140	110/120	130/140

a/ Stored in air at 73±3°F and 50±5% RH for 10 months after curing.
b/ Soaked once weekly for 15 weeks, then continuously for 3 days.
c/ Dried 5 minutes using I.R. heater at 4 inches above surface.

TABLE 9 EFFECTS OF SURFACE DRYING USING INFRARED HEATER—3-min HEATING

Slab	w/c	Initial Flow Air Dry a/ (mL/min)	Flow After Soaking b/ (mL/min)	Flow After Heat Drying c/ (mL/min)
A-2	0.38	45/50	30/35	45/50
B-2	0.43	60/70	45/50	65/75
D-2	0.60	130/140	70/80	120/130

a/ Stored in air at 73±3°F and 50±5% RH for 10 months after curing.
b/ Soaked once weekly for 16 weeks, then continuously for 3 days.
c/ Dried 5 minutes using I.R. heater at 4 inches above surface.

shorter heating times were not as promising, a 3-min heating time using the infrared heater at 4 in. above the test area was adopted.

Correlation Studies

In order to develop information on the relation between the SAF method and the more conventional techniques, a series of correlation studies was carried out. A set of comparison air-dry slabs was subjected to surface ponding on the finished surfaces with 15 percent sodium chloride for a period of 90 days. After exposure was complete, powder samples were obtained from the slabs at ¼-in. increments from the surface using procedures described in AASHTO T260. Using the procedure developed by Weyers (*16*), diffusion coefficients for chloride ions were obtained from the data. In addition, a series of cores of 4-in. diameter was obtained from selected air-dried slabs used for the initial SAF readings. The top 2 in. of each core was removed and used for the test specimens. The slices were dried to constant weight at 140°F, then tested for air permeability using a pulse-decay technique (*12*). Relationships between SAF readings, chloride diffusion coefficients, and air permeability are shown in Figure 4. The good correlations demonstrate that SAF can be used as a measure of true diffusion coefficients or permeabilities of the surface layer of concrete.

The relations shown in Figure 4 are not meant to imply that SAF testing can be used as a substitute for actual permeability measurements. If actual permeability values are desired, then the corresponding physical tests must be carried out.

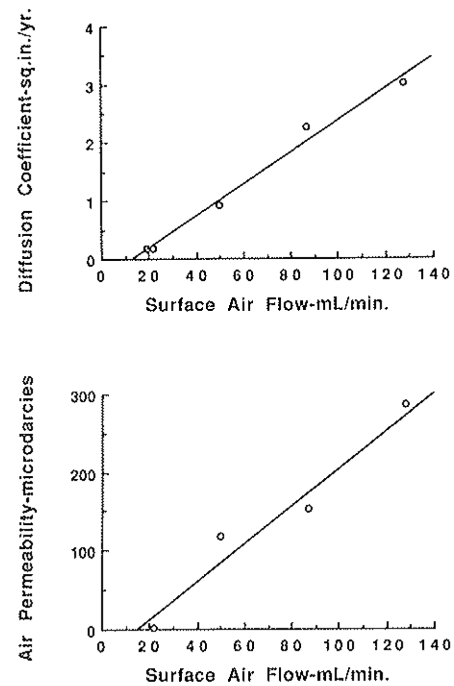

FIGURE 4 Relations between surface airflow readings, chloride diffusion coefficients, and air permeability.

DESIGN AND CONSTRUCTION OF A FIELD DEVICE

Design Criteria

In order to obtain a workable field technique, it was necessary to package the components into a fieldworthy prototype instrument. This field prototype required certain characteristics that would not necessarily have been included in the laboratory version of the device. Those characteristics were as follows:

- Ruggedness. It had to be water-resistant, resistant to accidental impact, and capable of transport in typical construction field vehicles.
- Portability. It had to be carried by one man, with total weight preferably less than 15 lb, and be capable of operating in horizontal, vertical, and overhead modes.
- Ability to operate from on-board power sources. A rechargeable battery source capable of powering the device for one working day was desirable. Although an on-board source was preferable, if this would degrade the portability of the device, an external source linked by cable to the device might be used.
- Rapidity of test and data collection. Although total test time (excluding setup or conditioning) for the laboratory device was only 1 min, it could be decreased even further if some of the manual operations, including timing of sequences such as opening and closing of valves, were automated. Onboard data acquisition was also considered; however, aside from the increased weight, and power requirements, the developers decided that this might be an unnecessary complexity to add to what was, in effect, a first-generation field instrument. The simple expedient of recording each data point on grid paper keyed to the structure (much as is done for most half-cell corrosion potential surveys) was considered to be adequate.

Construction of a Field Device

A conceptual drawing of a prototype field device is shown in Figure 5. The device is designed to use a dc vacuum pump powered by a rechargeable 12-volt Ni-Cad power supply. The flowmeter is an electronic mass flowmeter that utilizes the change in rate of heat flow through a heated tube to sense

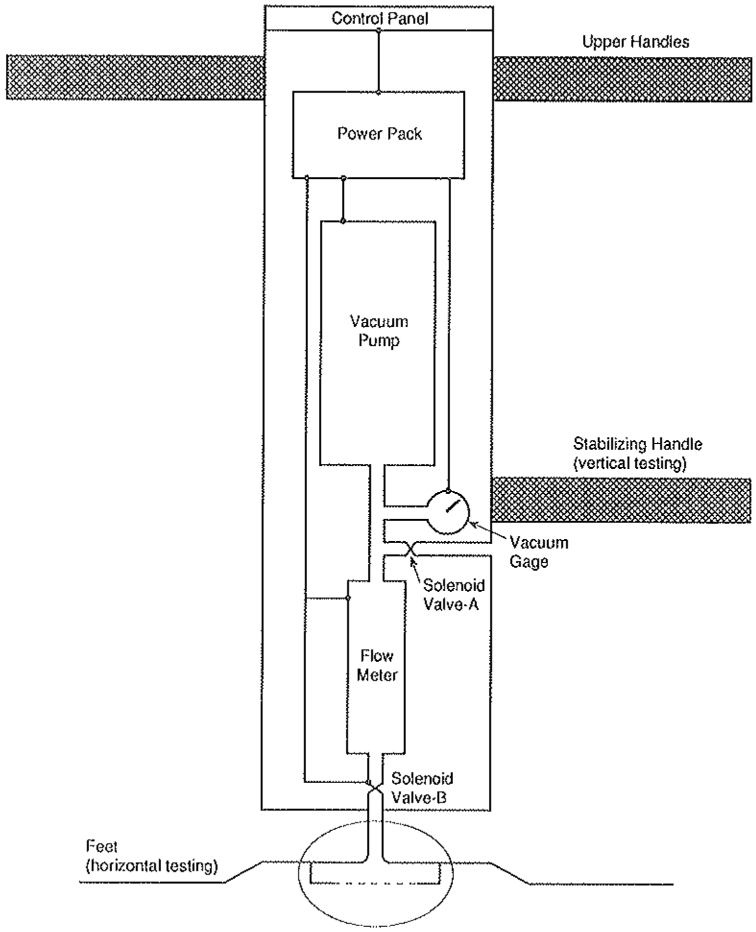

FIGURE 5 Conceptual drawing of a prototype field surface airflow device.

the mass flow through the sensor. By use of solenoid valves and electronic timers, the device is designed for one-man operation, and it is estimated that data could be gathered at the rate of approximately one test per minute. The field prototype was under construction in the summer of 1990 and field trials were planned after verification that the unit was operating properly.

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