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**Condition Evaluation of Concrete
Bridges Relative to
Reinforcement Corrosion**

**Volume 7: Method for Field
Measurement of Concrete
Permeability**

David Whiting
Construction Technology Laboratories, Inc.
Skokie, IL

Philip D. Cady
Pennsylvania Transportation Institute
The Pennsylvania State University
University Park, PA



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Program Manager: *Don M. Harriott*
Project Manager: *Joseph F. Lamond*
Copy Editor: *Katharyn Bine Brosseau*
PTI Technical Editor: *Joanne M. Fox*
Project Area Secretary: *Ann Saccomano*

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Strategic Highway Research Program
2101 Constitution Avenue N.W.
Washington, DC 20418

(202) 334-3774

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Abstract

A prototype surface air flow (SAF) device for the estimation of concrete surface permeability has been developed. The method measures the rate of air flow through a vacuum plate placed on a concrete surface under a vacuum of approximately 25 in. of mercury (16.6 kPa absolute pressure). The effective depth of measurement is approximately 0.5 in. (12 mm) 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.

A field prototype based on the SAF method was also developed. This portable field device operates off rechargeable nickel-cadmium (Ni-Cad) batteries. Reusable closed cell foam gaskets are used to ensure a tight seal to rough surfaces. A detachable vacuum plate can be used to obtain measurements on vertical or overhead surfaces. Readings can be obtained at the rate of approximately one per minute, allowing a large amount of information to be developed at close intervals across a given concrete member.

Executive Summary

While much of the interest in concrete permeability dates back to initial construction of hydroelectric structures in the 1930s, there is a renewed awareness of the role that permeability plays in the ultimate durability of concrete structures. Keeping moisture and aggressive substances from penetrating the concrete can minimize the effects of such distress mechanisms as freeze-thaw damage, sulfate attack, and corrosion of reinforcing steel.

While various methods are available for determination of concrete permeability in the laboratory, these are mostly time-consuming and require the removal of cores from the structure in question. Since coring is a destructive process, this limits the amount of information that can be obtained from a given structure. A number of more rapid, in situ techniques have been developed in recent years; however, many are at least semi-destructive, and the testing time may be slow on particular types of concrete.

The flow of air through a concrete surface can be used to characterize the permeability. The surface layer is especially important with regard to corrosion of reinforcing steel, since the temperature and shrinkage steel is often located less than 2 in. (50 mm) below the concrete surface. An indication of concrete surface permeability may be obtained by applying a temporary vacuum seal to the concrete surface and measuring the air flow (in ml/minute) under a vacuum of approximately 25 in. of mercury (16.6 kPa absolute pressure). That is, higher air flows would indicate a more permeable concrete, and conversely, lower air flows a less permeable concrete.

A laboratory device incorporating these principles was developed and applied to a series of concrete specimens covering a range of w/c ratios and associated permeabilities. Companion slabs were ponded with sodium chloride solutions in order to obtain chloride ion diffusion data. Cores were also obtained for measurement of air permeability using standard laboratory techniques. Correlation between the air-flow device and standard techniques was quite good, indicating that a rapid indication of concrete permeability could be obtained with the proposed technique.

By insertion of pressure wells into the test specimens, the effective range of the vacuum was found to be approximately 1/2 in. (12 mm) below the surface of the concrete. Therefore, the technique can be viewed as being most sensitive to the near-surface region. Moisture content of concrete was found to exert an influence on the test, but this can be minimized by surface drying prior to testing using a hand-held infrared heater.

Encouraged by the laboratory testing results, a portable field device that operates off rechargeable Ni-Cad batteries was developed. Reusable closed-cell foam gaskets are used to ensure a tight seal to rough surfaces. A detachable probe was developed to obtain measurements on vertical surfaces. Readings can be obtained at the rate of one per minute, allowing a large amount of information to be developed at close intervals across a given concrete member.

Field trials of the device were carried out during the first 6 months of 1991. Trials took place on bridges in the states of Pennsylvania and Texas. Bridge elements tested included decks, support beams, and pier caps. While some problems were encountered, mostly dealing with rough or cracked surfaces, the equipment in general performed satisfactorily. It was possible to test a 40-ft (12-m) long span in one lane over a period of about 2 hr using a test grid established on 3-ft (1-m) centers. Support elements can also be tested, although in many cases scaffolding, man lifts, or other devices may be needed to access elements beyond reach. In addition to the nondestructive testing, cores were obtained from a number of locations on each test structure and subsequently tested in the laboratory for air permeability. There was a general relationship between field measurements and actual air permeabilities. However, the relationship was not sufficiently quantitative to allow for prediction of actual permeabilities from the results of the field tests. The test must therefore be regarded as an indicator of relative permeability, and if more accurate values are needed, cores should be obtained and tested using more standardized laboratory techniques.

1

Introduction

Needs

Long-term durability of concrete structures may be directly related to the permeability of the concrete. If an aggressive substance 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, might be mitigated.

Highway industry interest in producing durable concrete has created a demand for rapid techniques capable of measuring the permeability of concrete to water and chloride ions. Measurement of the chloride ion permeability is by far the most important concern, as it is the chloride ion that promotes depassivation of the reinforcing steel, resulting in initiation of corrosion. While moisture is also needed for corrosion to be initiated, in most atmospherically exposed structures sufficient moisture is available from direct rainfall, snow melt, and runoff so that moisture contents at the level of the steel are usually sufficient for initiation of corrosion. Current tests for measurement of chloride ion permeability require either taking cores from the structure (1) or obtaining powder samples for subsequent chemical analysis (2). The latter is a viable option only if the structure has previously been exposed to chloride ions. Rapid, nondestructive tests are needed that could afford agencies with a profiled permeability across the structure without resorting to an unduly high number of cores or drill samples being taken from the structure in question.

Objectives

The objective of the research described here was to develop a rapid field test for concrete permeability that would correlate reasonably well with existing laboratory techniques. An emphasis was placed on correlation with permeability to chloride ions. It was recognized that any rapid, nondestructive field test would most likely not yield a true permeability (or chloride diffusion) value but would afford an empirical result that could be taken as a measure of relative permeability. The field test method was designed to be centered around a portable and self-contained device that does not require any disturbance of the concrete in order to obtain a test result.

Scope

The project's scope was:

1. demonstration of the principles of the device in a laboratory situation;
2. study of the influences of materials and environmental variables on test results;
3. correlation with other measures of permeability;
4. construction of a field device based on the laboratory prototype; and
5. evaluation of the device under actual field conditions.

2

Literature Survey

A literature survey of rapid permeability devices provided guidance from the experiences of others and ensured that devices meeting the criteria of the project had not already been developed.

As a first step, a position was adopted to view "permeability" in a broader context than simply that associated with saturated flow under a hydraulic gradient. Permeability may be viewed as the ability of a given concrete to resist penetration of a particular substance, be it liquid, gas, or ions. This ability may be expressed in absolute units of mass flow, by the amount of substance deposited in a given time, or as a relative ranking, depending on the particular test procedure employed.

Basic Mechanisms

The need for data on concrete permeability dates from the early 1930s, when designers of large hydraulic 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 D'Arcy's Law (3) as:

$$Q = \frac{k}{\mu} \cdot A \cdot \frac{dp}{ds} \quad (2-1)$$

where

- Q = volume outflow (cm³/sec)
- A = area (cm²)
- μ = viscosity (centipoise)
- dp/ds = pressure gradient (atmos/cm)
- k = permeability constant (D'Arcy's)

If the International System of Units (SI) is used throughout, then the permeability constant is expressed in terms of m². Primary factors influencing permeability were found to be water-to-cement (w/c) ratio and age of concrete. Glanville (4) noted a twentyfold decrease in permeability between 7 days and 12 months of age for a concrete with w/c ratio of 0.60. Recent studies by Gaerty and Freeman (5) and Whiting (6) have confirmed the importance of age of concrete on permeability, especially as regards the benefits of early moist curing on subsequent reductions in permeability. Permeabilities to such fluids as air (7), liquid nitrogen (8), methane (9), and oil (10) have also been measured. In general, permeabilities to gases are from one to two orders of magnitude greater than those for water, which is to be expected from comparative viscosities of the respective fluids.

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 capillary attraction, vapor transmission, or ionic diffusion. Data developed by Wing (11) and Dunagan (12) indicate that movement of water into dry concrete via capillary attraction can be quite rapid and that flow of water into a surface under low heads follows an inverse power law:

$$\frac{dr}{dt} = at^{-n} \quad (2-2)$$

where

- $\frac{dr}{dt}$ = flow rate (ml/s)
- t = time (in seconds)
- n = a dimensionless constant
- a = the volume of flow that has occurred at time t (ml)

An initial surface absorption test, ISAT (13), has been developed using these principles. Concern with corrosion of reinforcing steel promoted by chloride ions that penetrate through the concrete cover and eventually reach the reinforcement has resulted in research that has demonstrated that such migration of chloride ions occurs primarily through diffusion processes. Various studies (14,15) indicate the coefficient of diffusion to be on the order of 10^{-7} to 10^{-8} cm²/seconds. Diffusion will generally follow Fick's Second Law as:

$$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial X^2} \quad (2-3)$$

where

- C = concentration of distance x (in meters) from a boundary
- t = time (sec)
- D = effective diffusion coefficient (m²/seconds)

Procedures used to construct chloride profiles and determine diffusion coefficients for actual structures are discussed by Weyers and Smith (16). 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 (17), transient gas flow (18), or ionic conductance (19). While these methods offer a marked improvement in testing speed over previous steady-state techniques, they still require somewhat time-consuming specimen preparation and the removal of a core or powder sample from the structure, which makes testing a destructive process.

In Situ Test Methods

One of the first methods developed for field indication of concrete permeability was the ISAT (13).

The test apparatus consists of a gasketed cap, which is either clamped or affixed with sealing putty to the concrete test surface. Water is poured into the inlet until the outlet runs clear. A capillary tube is then affixed to the outlet tube, an initial reading is taken, and subsequent readings are obtained at 10 minutes, 30 minutes, 1 hour, and 2 hours. To date, the apparatus has been used on reinforced concrete, paving, and architectural concrete with good results.

The method has been standardized in BS 1881 Part 5-1970; recent revisions may eliminate the 2-hour measurement. In most on-site applications, measurements are often limited to the 10-minute reading. Problems encountered with the technique in the field include difficulties in achieving a watertight seal, securing the rig to the concrete (which may require the drilling of anchor-bolt holes in some instances), and inconsistent results during cold weather or when the surface was damp.

Since the initial development of the ISAT test, there has been an increased interest in development of test procedures for determination of in situ permeability. A number of non-steady state, or indirect, methods have been developed by a variety of researchers. Figg (20), Cather, Figg, et al. (21), Schonlin and Hilsdorf (22), Kasai et al. (23), and Hansen et al. (24) have concentrated on techniques based on non-steady state measurement of water absorption or air permeability.

Figg's (20) procedure consists of drilling a hole 1.2 in. deep x 0.2 in. (30 mm x 5.5 mm) in diameter into the concrete, sealing the hole with a silicone rubber plug, ensuring an air-tight seal with a hypodermic needle placed through the silicone plug, and then monitoring the rate of fall of water in a capillary after injecting water with the hypodermic syringe into the small cavity in the concrete.

The method has also been adapted to measure air permeabilities. The hole and sealant are the same as previously described for the water injection method. The run is started by turning the three-way stopcock to allow air to be withdrawn from the concrete until a vacuum of 112 mm Hg (14.8 kPa) is reached. The pump is then isolated and the time required for the pressure to rise to 150 mm Hg (19.9 kPa) is recorded. This value is taken as a relative measure of the air permeability of the concrete.

The results obtained were found to be a strong function of the moisture content of the concrete. Variations in moisture content from 1.0 to 1.8 percent led to a maximum difference in Δt of 20 seconds. Typical test times run from 100 to 500 seconds, indicating that errors of up to 20 percent are to be expected if the concrete has not been previously calibrated with respect to moisture content versus Δt . Although it is possible in the laboratory to determine moisture content by subsequent oven-drying (and thereby develop correction factors to the air permeability data), a satisfactory field technique is not as yet generally available (23).

Cather et al. recently (21) proposed modifications to the original Figg technique, which apparently result in an improved test procedure. A hole diameter of 0.4 in. (10 mm) and plug depth of 1.6 in. (40 mm) were selected. The pressure is reduced to 13 in. (330 mm) of Hg (43.9 kPa) and the time required for the pressure to rise 14.6 in. (370 mm) (49.2 kPa) is recorded on a digital manometer. Cather et al. concluded that within the period of the test, most of the pressure increase is due to air being drawn from a local area near the test hole rather than from the exterior surface of the test slab.

Scholin's test (22) consists of a 2.0-in. (50-mm)-diameter vacuum chamber (volume = V_s), which is placed on a smooth concrete test surface previously heated to about 122°F (50°C) for 5 minutes. Pressure is reduced to 0.02 to 0.20 in. (0.5 to 5 mm) Hg (.06 to .66 kPa) and then the vacuum pump is shut off. The time at which the pressure reaches a value of 1.5 in. (37 mm) Hg (4.9 kPa) is recorded as t_o . After 2 minutes, the pressure is recorded as P_1 . When the pressure reaches 230 mm Hg (30.6 kPa), a final time (t_1) is recorded. The permeability index is then given as:

$$M = \frac{(P_1 - P_o) \cdot V_s}{(t_1 - t_o) \cdot P_a \cdot (P_a - \frac{P_1 + P_o}{2})} \quad (2-4)$$

where

P_a = atmospheric pressure, and other quantities are as previously noted

A final category of in situ permeability techniques meriting discussion is the pressure-applied surface test developed by Montgomery and Adams (25)--the CLAM test. In this technique, a pressure vessel containing water is affixed to the concrete surface by means of a rapid-setting

epoxy adhesive. As water flows into the concrete, pressure is maintained by means of a vernier-controlled piston. Vernier readings before and after the test can then be used to indicate the amount of water flowing into the sample. This test is apparently simpler to apply than the ISAT or Figg methods; however, the need to glue the test rig to the concrete surface may result in some damage to the surface during removal.

Ranking of Techniques

The need for a rapid nondestructive technique led to the development of a number of criteria that should be met by any candidate technique and that could be used to rank existing and proposed methods. These include the following criteria, which were used to rank the previously cited methods as well as others uncovered during the literature search. A scale of -3 to +3 was used, with positive values indicating benefits of the technique in terms of the particular criteria and negative values indicating disadvantages.

- **Correlation**--The method should correlate either with long-term chloride ingress or with concrete characteristics known to be determinants of chloride ingress, such as w/c ratio, extent of curing, and use of permeability-reducing additives.
- **Interferences**--An ideal method would have no interferences; however, this may be unrealistic. If interferences are present, they may be manageable if they can be compensated for. The method will suffer otherwise.
- **Invasive**--If the method requires removal of concrete, or if substances will be injected into the concrete, the method may be considered invasive. An ideal method would rely on surface measurements with no substances injected into the concrete. On the other end of the scale, methods that rely on cores taken from the concrete would not be promising.
- **Mounting**--Methods that require mounting on a concrete surface will damage the surface and may be objectionable, especially on riding surfaces. Temporary types of bonding such as resilient adhesive or caulk may be less objectionable.
- **Rapidity**--Rough calculations indicate that an "instantaneous" method (i.e., one where each reading takes less than 10 sec) would enable one to profile two lanes of a typical bridge deck 100 ft (30 m) long at 3 ft (1 m) centers in 1 hour. One could do the same at 5-ft (1.5-m) centers if readings took less than 1 minute each. If readings took 5 minutes each, then a deck profile at 5-ft (1.5-m) centers would still be possible within 4 hours (1/2 day) of testing, which is not an unreasonable rate.

At over 10 minutes per reading, however, only 24 total readings could be obtained in the same time period. Obviously, slower tests reduce the amount of information obtainable.

- **Orientation**--Since substructures were included within the scope of the project, methods capable of being used in any orientation (horizontal, vertical, or overhead) are desirable. Methods relying on force of gravity or on containment of liquids (which is difficult in vertical or overhead configurations) suffer in this regard.
- **Weight**--A lightweight instrument is desirable, especially for substructure work.
- **Number of Components**--Reduction in the number of components results in reduced time needed for set up and reduced complexity. A self-contained unit is the ideal case, though this may be impractical if locations with difficult access are to be tested.
- **Power**--Units not requiring electrical power or capable of operation on standard low-voltage batteries are desirable. AC power requires gas generators and makes testing more cumbersome.
- **Number of Operators**--The ultimate cost of the test will increase with the number of operators required. A small unit that can be operated by one person is the ideal.
- **Operator Skill**--Highly skilled personnel are not always available. Simple units that can be operated by relatively unskilled personnel would be ideal.

Test methods were scored using these criteria, and the results are presented in Table 2-1.

The air permeability methods offer considerable advantages in terms of many of the criteria deemed important for an on-site method. On the average, they scored fairly high on correlation with such parameters as w/c ratio, strength, and extent of curing. Interferences are something of a problem, the predominant one being moisture content prior to testing. This is more of a problem for methods relying on drilled holes than for surface methods, since the surface layer can be dried prior to testing in a fairly short time period. The methods are invasive when drilled holes are used, but not for the surface types. Mounting is generally not required. The methods are not overly rapid, but one might expect to make some improvements in this area. Air permeability methods score fairly high on orientation and weight, but many are "first generation" systems utilizing components rather than finished

Table 2-1. Ranking of in situ permeability methods.

Method	Ranking (Point Score)	Reference
Figg air permeability and modifications	(+3) to (+6)	20, 21, 23
Hansen surface air pressure	(+2)	24
Schonlin surface vacuum	(+11)	22
Mini-permeameter for rock cores	(+21)	26
ISAT	(+3)	13
Figg water absorption	(0)	13
Pressure injection of water	(+4)	25

packages. The general lack of need for AC power is favorable, and the operator skill required would generally be at the technician level.

Methods based on water permeability are somewhat less promising. Correlations are not as good, and moisture appears to have a more serious interference effect. Because most of the water methods operate from the surface, they are, on the average, somewhat less invasive than the air techniques. However, most do require mounting and are fairly slow. Limits on orientation are a problem. In terms of overall weight, number of components, and power requirements, they are similar to the air methods. Operator skills are expected to be similar.

In summary, the most promising avenue of approach for development of a permeability technique appeared to be a technique based on air permeability, which can be operated from the surface and requires no mounting. A rapid flow-measurement type technique similar to the "mini-permeameter" was very appealing, as wide-range electronic flow meters are capable of spanning the entire range of flows to be expected, reducing the need to allow for very long decay times, as appears to be the case for the vacuum decay techniques. The remainder of this report describes development and testing of a device based on these findings.

3

Method Development

Basis and Bench Prototype

The 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 forcing air into the concrete, which would require a direct pressure seal to be created at the surface, the technique relies on the creation of a vacuum at the surface. The vacuum causes air to flow out of the concrete along the pressure gradient. SAF uses the rate of flow of air for a rapid measurement once the desired pressure differential has been achieved. The technique was designed to give an indication of permeability for a wide variety of concrete materials. These include very low permeability concretes such as those containing silica fume or polymer modifiers as well as very high permeability concretes that result when high w/c ratio and/or poor curing practices are employed. The effective test area was chosen as a circle 2.75 in. (70 mm) in diameter, offering a representative test on a small area of most structural concretes. The test was designed to be applicable to support and substructural elements as well, necessitating that the device also be operable in vertical and overhead modes.

To evaluate the basic concept of the device, it was deemed prudent to construct a laboratory bench prototype prior to assembly of an actual field test instrument. A schematic diagram of the laboratory bench prototype is shown in Figure 3-1. The 4-in. (102-mm) diameter steel vacuum plate is fitted with a 0.125-in. (3-mm) thick soft rubber ring allowing for a circular flow area 2.75 in. (70 mm) in diameter. Flow is initially directed through Valve A until the

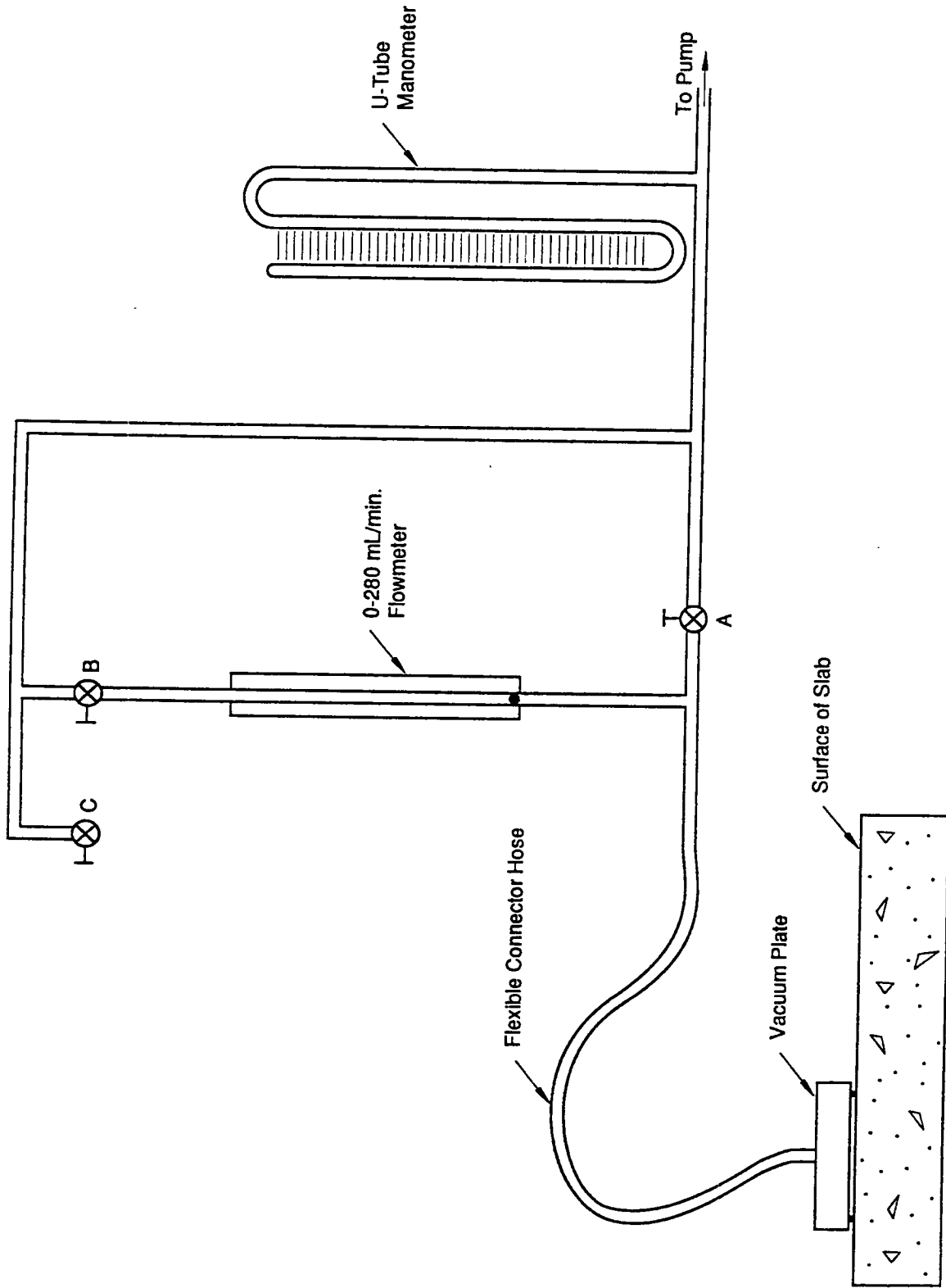


Figure 3-1. Schematic drawing of the laboratory SAF device.

system reaches the operating pressure of 120 to 140 mm Hg (15.9 to 18.6 kPa) as measured on the vacuum gage (a U-tube Hg manometer was used in the bench version). Valve A is then closed and the air steam is directed through Valve B from the rotameter (flowmeter), which is calibrated to read in units of ml/minute over a range of 1 to 280 ml/minute. The total test time is approximately 1 minute, at which time the pump is turned off and air is allowed to reenter the system through Valve C.

Design and Preparation of Test Specimens

After initial system checkouts were complete, a series of concrete test specimens designed to offer a range of permeabilities were designed and constructed. The majority of specimens consisted of plain (unreinforced) slabs 12 x 24 in. (305 x 610 mm) in width and length and 6-in. (152-mm) thick. A few reinforced slabs were constructed in order to determine the effects of reinforcement cover on the test procedure. These slabs contained No. 5 (12-mm) rebar mats positioned 0.5 and 1.5 in. (12 and 37 mm) below the top surface of the slab. Additionally, in a few of the slabs, brass tubes 0.156 in. (4 mm) in diameter were positioned 0.25, 0.5, and 1 in. (6, 12, and 25 mm) from the surface to be used to measure extent of depth of influence of the vacuum. Thermocouples were embedded 0.25, 0.5, 1, and 2 in. (6, 12, 25, and 50 mm) below the top surface.

The concrete mixtures used are shown in Table 3-1. The mixtures were proportioned so as to obtain a relatively wide range of permeabilities, while still remaining within the spectrum of mixtures that could reasonably be expected to be encountered in actual field practice.

Slabs from Mixtures A through D were maintained under wet burlap/polyethylene overnight, then transferred to heavy plastic bags for 28 days of curing. This was done in an attempt to simulate actual field conditions. Although curing membranes may be used to retain moisture to aid in curing, additional moisture is generally not deliberately provided to the slabs over long periods of time. In contrast to Mixtures A through D, Mixture E was fully moist-cured for 28 days to ensure that concrete having a high level of impermeability would be included in the study. Following recommended practice for latex modified concretes (LMC), Mixture F was exposed to air drying immediately after demolding, in order to develop maximum curing of the latex admixture.

Table 3-1. Concrete test mixtures.

Mix	Quantities--lb/yd ³				Water/ Cement Ratio	Admixture	Slump (in.)	Air (%)
	Cement	Sand	Gravel	Water				
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

*No admixtures other than air-entraining agents used.

Note: 1 lb/yd³ = 0.59 kg/m³; 1 in. = 25.4 mm; 1 lb = 0.454 kg; 1 gal = 3.785 L.

After the conclusion of initial curing, the slabs were coated on the four edges with moisture barrier grade epoxy and placed in the following environments:

- Continuous air drying at 73 ± 3°F (23 ± 1.7°C) and 50 ± 5-percent RH (air-dry series); and
- Cycling of 1 day wet burlap applied to top surface at 75 to 80°F (24 to 27°C) and 6 days drying (moist cycle series).

Slabs containing reinforcement was exposed to continuous air drying only.

Preliminary Testing of Bench Prototype

Air-Dried Test Series

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

taken on a rectangular grid of 3- x 4-in. (75- x 100-mm) cells avoiding the outermost cells so as to minimize possible edge effects. Results are given in Table 3-2.

Table 3-2. SAF measured on air-dried slabs.

Slab	Readings	Face	Air Flow (ml/minute)			Std. Dev.	% C.V.
			Mean	Minimum	Maximum		
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	— ^b	— ^b	— ^b	— ^b	— ^b
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

^aSlab not tested due to surface crazing.

^bNo reading.

The lowest readings were obtained for the silica fume concrete (E), and the highest for the concrete with w/c = 0.6 (D). Readings for LMC (F) were somewhat higher than for silica fume, as would be expected. Conventional concretes exhibited an increasing surface air flow with increase in w/c, at least on the finished face. There was little difference in air flow between concrete Mixtures A, B, and C on the cast face, perhaps representing an increased densification at the bottom of the slab due to 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 offscale (i.e., >280 ml/minute), and those that fell onscale were unstable. Since it was believed that this might have been due to leakage around the

gasket, a silicone vacuum grease was applied to the gasket and some readings were repeated. This stabilized some readings but most were still offscale. Upon inspection of the surface that had been coated with grease, a fine network of surface microcracks in the thin surface paste layer became 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. Repeat testing, however, still indicated microcracks, which were now even more visible on the sandblasted surface. It is possible that this slab may have been prematurely finished, or suffered from some plastic shrinkage cracking.

The statistics reported in Table 3-2 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 due to hand finishing across the slab. To obtain a better estimate of test reproducibility, a series of measurements consisting of five replicates on each of three positions on cast and finished surfaces of each slab was performed. Summary statistics are given in Table 3-3 for the cast faces.

The variability of successive measurements at one position is much less than the variability across the slab. This indicates that the method actually detects differences in permeability across the surface of the slab, most likely due to small differences in consolidation and finishing across the surface. Reproducibility statistics are not shown for Slab F-1 (latex concrete). This is 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 such that when it was removed, a 1-in. (25-mm) long by 0.156-in. (4-mm) deep cavity was created at the 0.5- and 1-in. (12- and 25-mm) depths. A microflowmeter and a manometer were attached to each well in order to measure air flow and vacuum level at each depth. Results are given in Table 3-4.

Table 3-3. Measurement of SAF test repeatability.

Slab	Face	Air Flow (ml/minute)			
		Position	Mean	Std. 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

For low w/c concrete (Slab A-2), only very small flow rates could be measured, even 0.25 in. (6 mm) below the surface. For a slightly higher w/c ratio (Slab B-2), flow at 0.25 in. (6 mm) below the surface was approximately 20 percent of the surface reading. For high w/c ratio concrete, flow was much greater at 0.25 and 0.50 in. (6 and 12 mm) and was even detectable 1 in. (25 mm) below the surface. These results indicate that while the effective test depth is somewhat dependent on the characteristics of the particular concrete under test, the test is predominantly influenced by the near-surface (less than 0.5 in. [12 mm]) region of the concrete cover.

Table 3-4. Effective depth of vacuum penetration.

Slab	Well Depth (in.)	Air Flow (ml/minute)	Vacuum (mm Hg)
A-2	Surface	40.0	-635
	0.25	1.0	— ^a
	0.5	0.5	— ^a
	1	0.0	— ^a
B-2	Surface	65.0	-635
	0.25	12.6	-180
	0.5	2.1	— ^a
	1	0.0	— ^a
D-2	Surface	130.0	-635
	0.25	100.0	-180
	0.5	13.5	-160
	1	0.4	— ^a

^aNo vacuum detected.

Note: 1 in. = 25.4 mm; 1 mm Hg = 0.0133 kPa.

Effects of steel placement and cover on air flow permeability readings were also investigated. Readings were taken directly above and between No. 5 (16-mm) bars having 0.5 and 1.5 in. (12 and 30 mm) of cover and spaced at 5-in. (127-mm) centers. Results are compared in Table 3-5. 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 0.5 in. (12 mm) or greater.

Table 3-5. Effects of steel placement and concrete cover.

Slab	Air Flow (ml/minute)			
	0.5-in. Cover		1.5-in. Cover	
	Above Bars	Between Bars	Above Bars	Between Bars
A-2	50	50	40	40
B-2	— ^a	— ^a	60	65
D-2	155	145	135	130

^aNo stable readings obtainable (crack in concrete above bar).

Note: 1 in. = 25.4 mm.

Moist-Cycled Series Test Slabs

Testing was performed on the slabs aged 28 days then subjected to a weekly wetting cycle (1-day soak, 6-day air dry). The top (finished) surface of each slab was subjected to the soaking, and the bottom (cast surface) was protected from direct wetting during the soak, but was in a damp environment. Surface air flow tests were performed on both cast and finished surfaces approximately 1 hour after the removal of the soaking blankets. Test results are presented in Table 3-6.

For the finished surface, lower readings were encountered for the moist-cycled slabs. The difference between dry and moist cycle mean readings ranged from about 15 ml/minute for slabs prepared from Batch A to 30 ml/minute for slabs prepared from Batch D. Differences for cast surfaces were less, as the cast surfaces were not directly exposed to liquid water. 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

Table 3-6. Comparison of SAF test results on air-dried and moist-cycled slabs.

Batch	Slab	Face	Condition ^a	Air Flow (ml/minute)		
				Mean	Minimum	Maximum
A	A-1	Cast	Dry	67	55	85
		Finished	Dry	50	40	65
	A-4	Cast	Damp	60	45	70
		Finished	Moist cycled	45	25	75
B	B-1	Cast	Dry	68	55	90
		Finished	Dry	87	60	155
	B-4	Cast	Damp	65	48	95
		Finished	Moist cycled	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	Moist cycled	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

^aSlabs surface-dry at start of test.

were considerable differences due to wetting of the test surfaces. These differences were greatest for the high w/c concrete (D-4), and were insignificant for very low permeability concretes (E-2 and F-2).

A summary of air flow measurements on the various sets of test slabs under differing conditions of moisture is given in Figure 3-2. In spite of the differences induced by varying surface conditions and moisture levels, a general trend of increasing air flow with decreasing "quality" of concrete was seen. The concretes designed to have low permeabilities (Batches E--silica fume, and F--LMC) do have the lowest air flows. Conventional concretes typical of those specified for structural and paving application (Batches A, B, and C) showed a slight upward trend for air flow as the w/c ratio is increased going from Batch A to Batch C. The poorest quality concrete produced in this test series (Batch D) exhibited the highest air flow reading.

A preliminary classification of permeability based on air flow measurements is suggested by Figure 3-2. Readings less than 30 ml/minute are associated with low permeability concretes. Readings between 30 and 80 ml/minute are associated with moderately permeable concrete (w/c from about 0.40 to 0.5). Readings above 80 ml/minute are associated with high permeability concretes. Readings in "borderline" regions may be ambiguous, for instance, very wet high w/c concretes may on occasion give readings closer 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 strategies were carried out. A 12- x 2- x 4-in. (304- x 305- x 102-mm) louvered sheet metal box was mounted on a slab so that an embedded thermocouple "tree" (1/4-, 1/2-, 1-, and 2-in. [6-, 12-, 25-, and 50-mm] thermocouple depths) was at the approximate center of the area. An electric heat gun (1500 W capacity) was then placed into 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 3-3. Profiles for other slabs tested were quite similar. While surface temperatures reached close to 300°F (149°C), temperatures at 0.25, 0.5, and 1 in. (6, 12, and 25 mm) peaked at approximately 140, 110, and 95°F (60, 43, and 35°C) after 5 minutes of heating. The slab was then allowed to cool for an additional 10 minutes until all temperatures fell below 90°F (32°C). At this time, air flow tests were repeated. Results are given in Table 3-7.

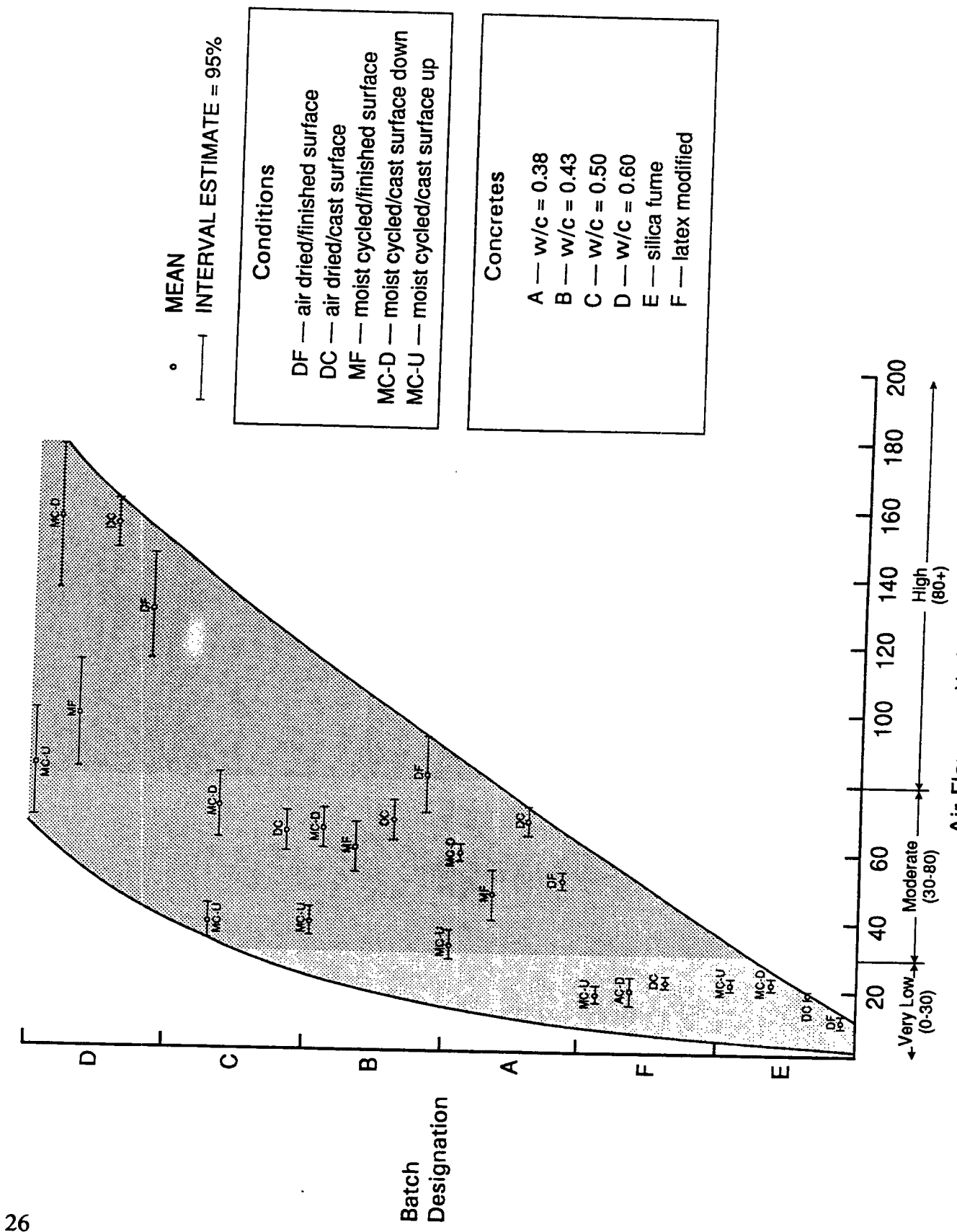


Figure 3-2. Preliminary classification of permeability based on SAF measurements.

Table 3-7. Effects of surface drying using 1500 W electric heat gun.

Slab	w/c	Initial Flow Air Dry ^a (ml/minute)	Flow After Soaking ^b (ml/minute)	Flow After Heat Drying ^c (ml/minute)
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

^aStored in air at $73 \pm 3^\circ\text{F}$ ($23 \pm 1.7^\circ\text{C}$) and 50 ± 5 -percent RH for 10 months after curing.

^bSoaked once weekly for 7 weeks, then continuously for 3 days.

^cDried 5 minutes using 1500 W heat gun 4 in. (100 mm) above surface.

These results 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 seems to have on the test. The 1500 W heat gun requires a high energy expenditure, and would necessitate that a relatively large generator be transported to the test site. In order to provide for more compact equipment, the use of a small hand-held liquid propane-fired infrared (IR) heater (such as is used for stripping paint) was investigated. The heater was held 4 in. (100 mm) over the desired test areas for periods of 5 minutes each. The heating profiles, also shown in Figure 3-3, compare favorably with the profiles obtained using the heat gun. After cooling, SAF measurements were made on the heated areas. Results are presented in Table 3-8.

Table 3-8. Effects of surface drying using IR heater after 5 minutes of heating.

Slab	w/c	Initial Flow Air Dry ^a (ml/minute)	Flow After Soaking ^b (ml/minute)	Flow After Heat Drying ^c (ml/minute)
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	110/120	130/140

^aStored in air at $73 \pm 3^\circ\text{F}$ ($23 \pm 1.7^\circ\text{C}$) and 50 ± 5 -percent RH for 10 months after curing.

^bSoaked once weekly for 15 weeks, then continuously for 3 days.

^cDried 5 minutes using IR heater 4 in. (100 mm) above surface.

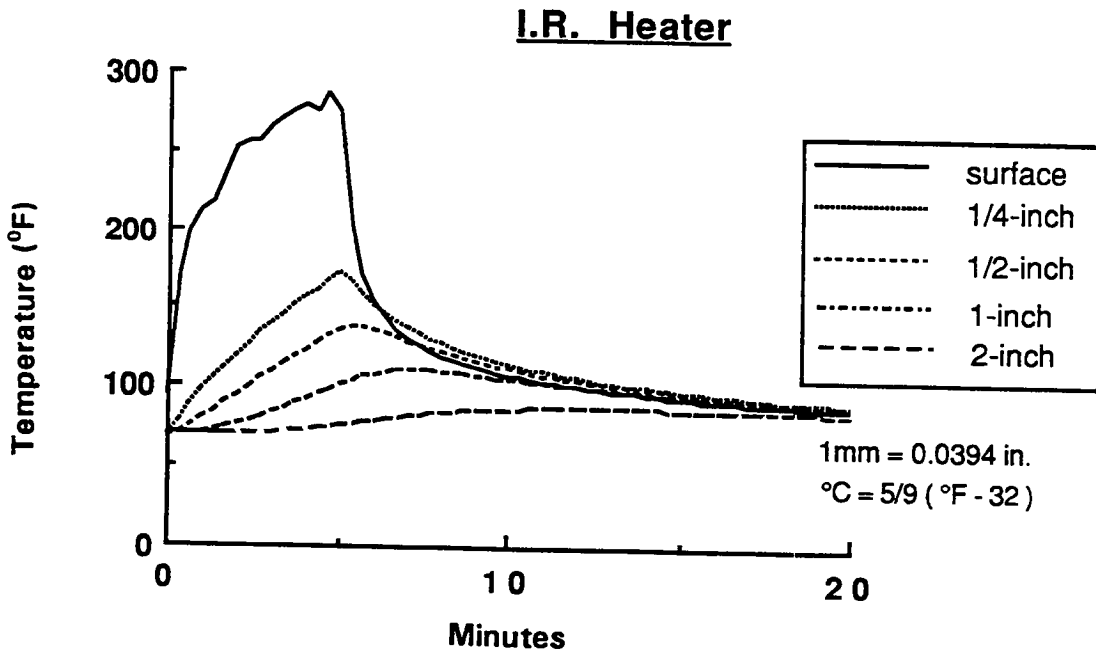
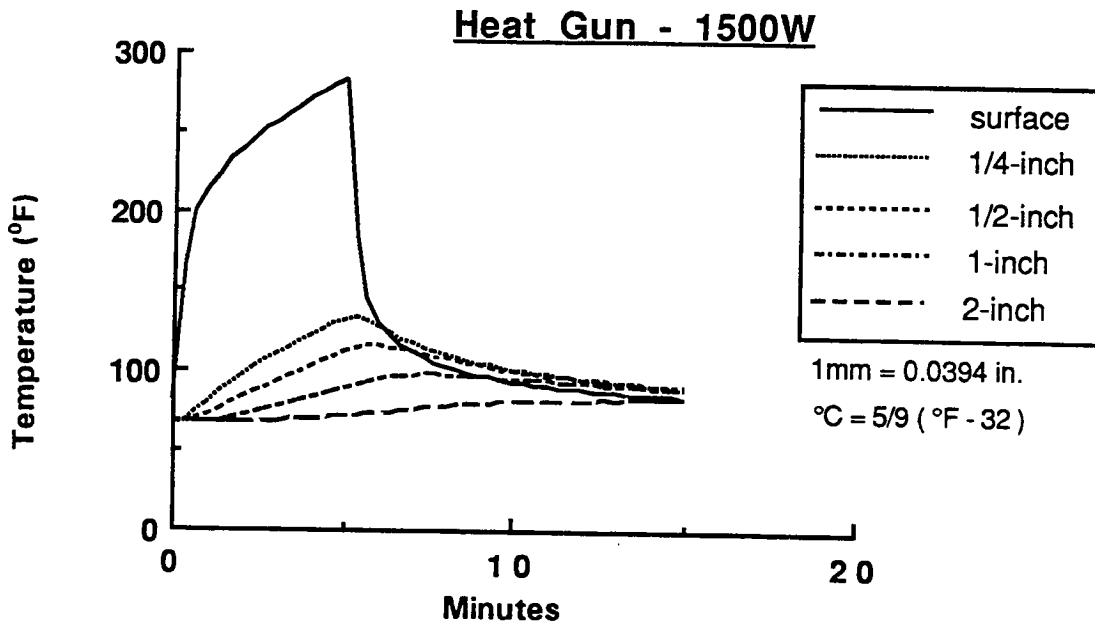


Figure 3-3. Comparison between temperature profiles generated using the heat gun and IR heater.
 28

The data demonstrate that the IR method is capable of restoring the test area to essentially the initial air dry condition after 5 minutes of heating.

Examination of Figure 3-3 indicates that essentially the same temperatures at any given depth are reached after 3 minutes using the IR heater, compared to 5 minutes using the heat gun. To investigate the possibility of using shorter heating times, the slabs were re-wetted and the tests carried out using 3 minutes of heating with the IR heater. Results, shown in Table 3-9, were again very favorable, indicating that a 3-minute heating time could be used. Further tests at shorter heating times were not as promising; therefore, a 3-minute heating time using the IR heater 4 in. (100 mm) above the test area is recommended in cases where testing is to be carried out on a wet surface.

Table 3-9. Effects of surface drying using IR heater after 3 minutes of heating.

Slab	w/c	Initial Flow Air Dry ^a (ml/minute)	Flow After Soaking ^b (ml/minute)	Flow After Heat Drying ^c (ml/minute)
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

^aStored in air at 73 ± 3°F (23 ± 1.7°C) and 50 ± 5-percent RH for 10 months after curing.

^bSoaked once weekly for 16 weeks, then continuously for 3 days.

^cDried 3 minutes using IR heater 4 in. (100 mm) above surface.

While the surface-heating technique is workable, it does dramatically increase the time needed to carry out a single test. It was recognized that when testing is being carried out by local forces, it is often possible to schedule around periods of inclement weather, thus providing a window of drying time prior to initiation of testing. To investigate the minimum "natural" drying times needed subsequent to cessation of a wet period, a series of moist-cycled slabs were selected that had previously been placed at 100°F (38°) under forced air flow for a period of 2 weeks, then stored at 73 ± 3°F (23 ± 1.7°C) and 50 ± 5-percent RH for a period of approximately 8 months. SAF tests were carried out on these slabs, and the slabs then re-introduced into the moist cycle for a period of 6 weeks. The slabs were then subjected to 24 hours of drying at 75°F (24°C) with an RH of 25 percent. A low-speed fan was used to gently circulate air over the specimens during the drying period.

Results of SAF tests carried out immediately prior to moist cycling (initially dry condition) and following the 24-hour dry period after moist cycling are shown in Table 3-10.

Table 3-10. Effects of "natural" drying on SAF.

Slab	w/c	Initial Flow Prior to Moist Cycling (ml/minute)			Flow After Drying for 24 Hours Subsequent to Moist Cycling (ml/minute)		
		Mean ^a	Max	Min	Mean ^a	Max	Min
B-4	0.43	102	150	65	100	155	60
D-4	0.60	142	195	115	130	200	105

^aAverage of 15 readings across surface of slab.

Results indicated that flows could be restored essentially to the original air-dried values through gentle drying at 75°F (24°C) for 24 hours. It is recognized that the indoor relative humidity where these tests were carried out was relatively low and that this would tend to accelerate drying as compared to conditions normally encountered in temperate climates during summer months, where average relative daytime humidity would typically range from 50 to 70 percent. However, the indoor tests did not take into account the radiant effects of direct sunlight, which can raise surface temperatures by significant amounts and thereby greatly increase rapidity of drying. Since all potential field conditions cannot possibly be investigated, our recommendations are that SAF tests can be carried out under temperate conditions (i.e., late spring to early fall) provided the concrete is exposed to drying conditions for at least 24 and preferably 48 hours subsequent to any rainfall that wets the concrete surface to a saturated condition.

Correlation Studies

Specimen Preparation

In order to develop correlations between SAF and other methods, companion test specimens were prepared. The first set of plain air-dried slabs was used to prepare these specimens.

Each slab was dry-cut into two 12- x 12- x 6-in. (305- x 305- x 15-mm) sections. One of each of these half-slab sections was used to obtain a series of 4-in. (102-mm) diameter full-depth cores. On the second section, a 0.5-in (12-mm) wide foamed polystyrene dike was affixed to the top (finished) surface using silicone caulk. These specimens were then subjected to the test procedures described below.

Test Procedures

A 15-percent solution of sodium chloride was prepared and poured into the diked section of each half-slab. The slabs were placed in an environment maintained at $70 \pm 3^\circ\text{F}$ ($23 \pm 1.7^\circ\text{C}$) for a period of 90 days. The specimens were covered with polyethylene sheeting to reduce evaporation of the solution, which was brought to its initial level at weekly intervals. After 90 days of ponding, the solution was removed from the slabs, a brief rinse of tap water was used to remove residual salt from the surface, and the slabs were allowed to air-dry.

Two 1.125-in. (28-mm) diameter holes were then drilled into the surface of each slab. Powder was removed at the following depths: 0 to 0.375 in. (0 to 9 mm), 0.375 to 0.625 in. (9 to 16 mm), 0.625 to 0.875 in. (16 to 22 mm), 0.875 to 1.125 in. (22 to 28 mm), and 1.125 to 1.625 in. (28 to 41 mm). Samples were then analyzed for total chloride ion using procedures described in AASHTO Specification T 260 (2). Results were then averaged for each set of duplicate samples. Data were then transmitted to Professor Richard Weyers, who has developed (16) an analytical procedure for obtaining chloride diffusion coefficients (D_c) by fitting the experimental data to Fick's law of diffusion. Results are presented in Table 3-11.

Table 3-11. Chloride diffusion constants (D_c) for test slabs.

Slab	w/c Ratio	Admixture	D_c (in. ² /yr)
A	0.38	— ^a	0.93
B	0.43	— ^a	2.27
D	0.60	— ^a	3.01
E	0.36	Silica fume	0.19
F	0.27	Latex	0.18

^aNo admixtures other than air-entraining agents used.

Note: 1 in.²/yr = 4.88×10^7 mm²/second.

Three of the 4-in (102-mm) cores from each of the second half-slabs for each concrete were sliced in order to remove the top 2-in. (50-mm) portion. These 4-in. (102-mm) diameter x 2-in (50-mm) thick slices were placed in a forced draft oven maintained at $140 \pm 5^\circ\text{F}$ ($60 \pm 2.8^\circ\text{C}$) and dried to constant weight. Drying time was approximately 20 days. Each slice was then wrapped carefully in moisture-resistant packaging and shipped to Core Laboratories, Inc. in Dallas, Texas. Slices were then tested for air permeability using a pulse decay permeameter. Details of the theory, test equipment, and procedures are given by Bourbie and Walls (27). With this equipment, permeability can be measured from 1 millidarcy ($10^{-3} \mu\text{m}^2$) to 10 nanodarcy ($10^{-8} \mu\text{m}^2$) with an accuracy of ± 5 percent. Results are given in Table 3-12.

After air permeability testing had been completed, the cores were packaged and shipped to the University of Toronto for water permeability testing. The cores were cut to a length of 1.5 in. (40 mm) so they could be accommodated into the test fixture. They were then vacuum saturated with water just prior to testing. Testing was carried out using a pulse-decay water permeameter developed at the university. Results are presented in Table 3-13.

Comparisons of Results

Relationships between SAF readings, chloride diffusion constants, and air and water permeabilities are shown in Figure 3-4. Correlations are good and demonstrate that SAF can be used as a qualitative measure of chloride diffusion coefficients or permeabilities of the surface layer of concrete. One should be aware that the relationships shown in Figure 3-4 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.

Table 3-12. Air permeability as determined from pulse-decay measurements.

Slab	w/c Ratio	Admixture	Air Permeability (microdarcsies)
A	0.38	— ^a	134
B	0.43	— ^a	147
D	0.60	— ^a	286
E	0.36	Silica fume	11
F	0.27	Latex	1

^aNo admixtures other than air-entraining agents used.

Note: 1 microdarcey = $10^{-6} \mu\text{m}^2$.

Table 3-13. Water permeability as determined from pulse-decay measurements.

Slab	w/c Ratio	Admixture	Water Permeability (pm/sec)
A	0.38	— ^a	3.00
B	0.43	— ^a	7.30
D	0.60	— ^a	6.10
E	0.36	Silica fume	0.75
F	0.27	Latex	0.36

^aNo admixtures other than air-entraining agents used.

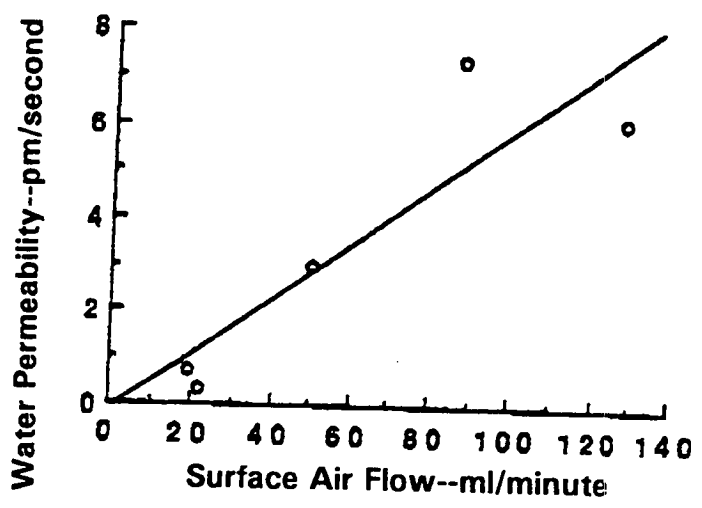
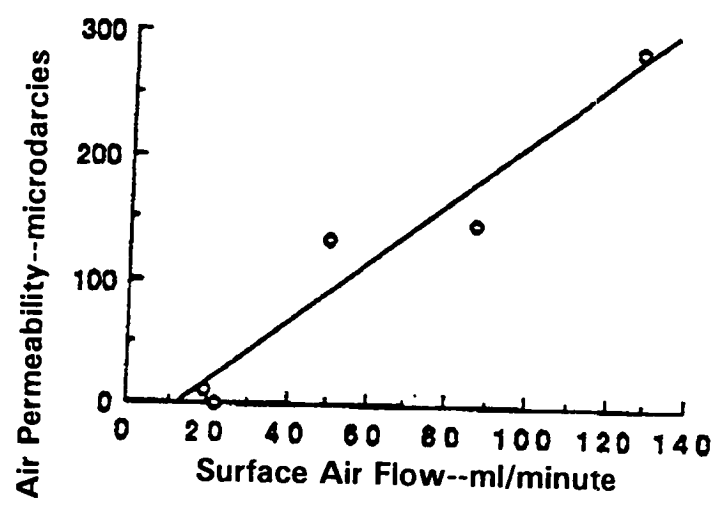
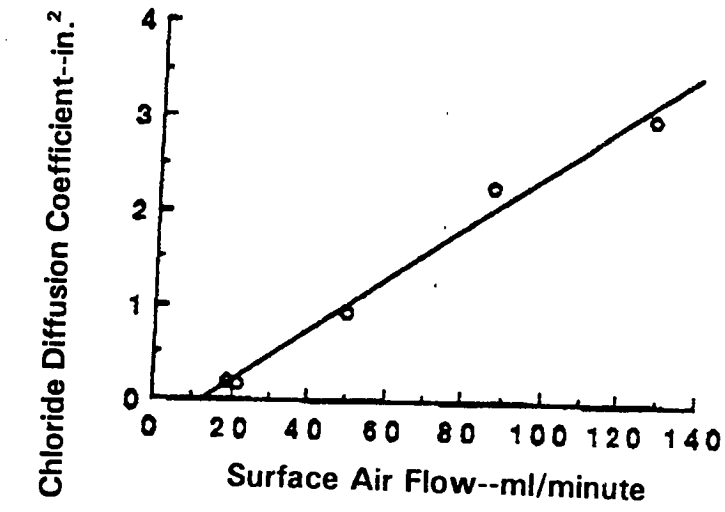


Figure 3-4. Relationship between SAF, chloride diffusion coefficients, and air and water permeabilities.

4

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 part of the laboratory bench version of the device. The characteristics believed to be most important for successful development of a field device included:

- **Ruggedness.** The instrument must be water resistant, resistant to accidental impact, and capable of transport in vehicles typical of those used on construction sites.
- **Portability.** The instrument should be able to be carried by one person, with total weight preferably less than 15 lb (33 kg), and capable of operation in horizontal, vertical, and overhead modes.
- **Power Sources.** The instrument should be capable of operation from on-board power sources. A rechargeable battery source capable of powering the device for one working day and able to recharge overnight was deemed highly desirable.
- **Rapidity of Test.** While total test time for the laboratory device was less than 1 minute, the sequence of opening and closing of valves during extensive field testing might become quite tedious. Automation of these functions was deemed to be an important feature.

- **Safety of Test.** The device should not use any dangerous voltages, hazardous chemicals, or unshielded moving parts. The basic principles of the SAF method made for an inherently safe procedure, and no problems were expected in this regard.

Construction of Field Prototype Device

The aforementioned criteria and a general description of the principles and desirable configuration of a field device for carrying out the SAF test procedure on concrete structures were submitted to a number of firms having expertise in development of test equipment for construction applications. Based on a review of designs submitted and other selection criteria, Texas Research Institute (TRI), Austin, Texas was selected to construct the device. Construction took place over a period of 18 months, during which first-generation instruments were tested and modified so as to meet the intended goals. In order to obtain the desired characteristics, some sacrifices in the portability of the device had to be made.

The final weight and configuration of the unit made it impractical for one-man operations on vertical or overhead surfaces. For this reason, an auxiliary lightweight vacuum plate was developed, which was capable of remote operation from the unit using a connecting vacuum hose.

Descriptions of overall features, major internal components, overall electronic circuitry, and operations of the device are given in this chapter and in the appendices to this report. Further details, including detailed circuit diagrams and a troubleshooting guide, are given in the operations manual supplied with the instrument.

Overall Features

Figure 4-1 is an outline drawing showing the dimensions of the device and major external features. There are two folding handles on the device to hold it in a vertical position while testing horizontal surfaces such as bridge decks. These two handles also contain switches used to operate the unit. The right handle contains two miniature switches. One switch activates a solenoid valve, which directs vacuum to the plate at the foot of the device. The other switch is strictly electronic and allows the operator to "hold" the readings, which are

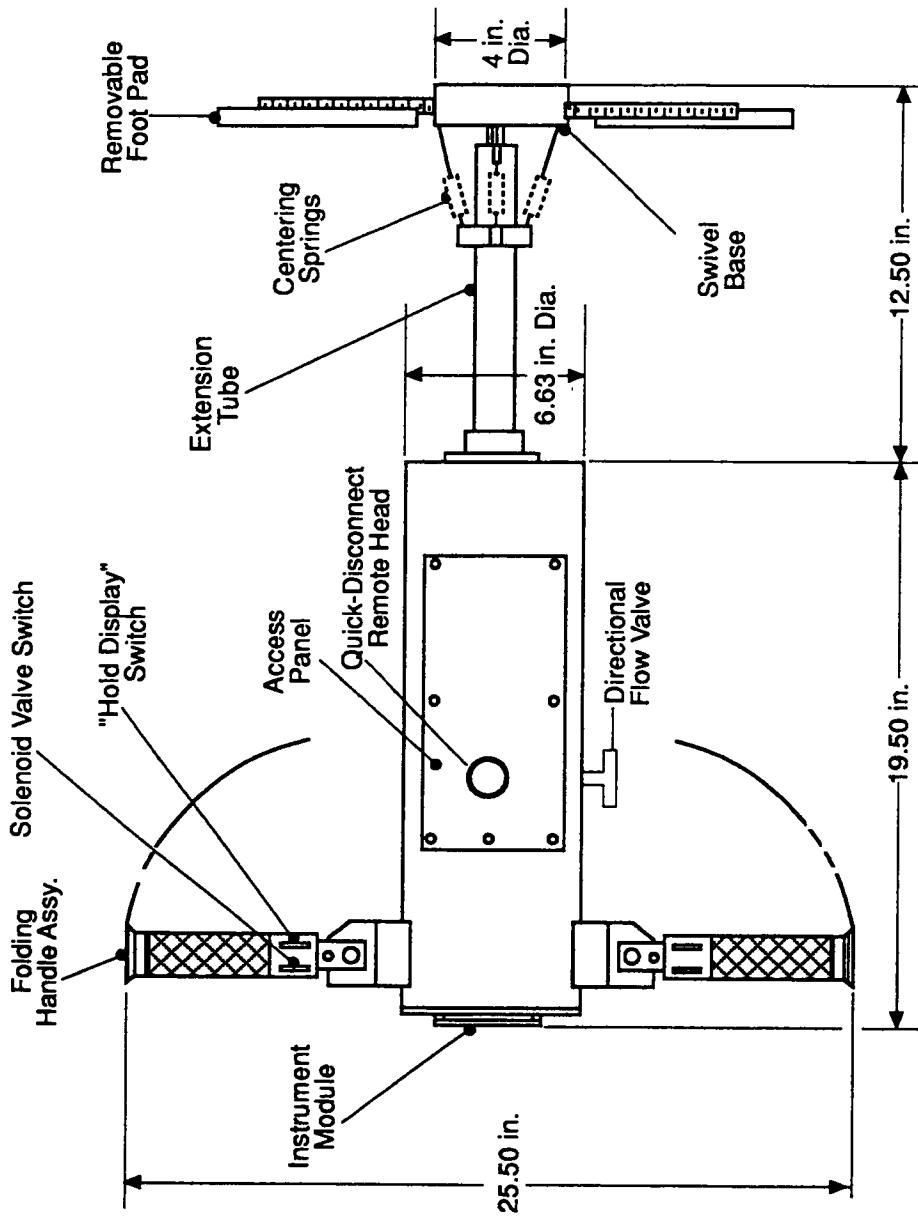


Figure 4-1. Outline drawing of the permeability indicator.

displayed on the panel meters at completion of the test. Both handles fold out of the way for compact storage. The vacuum plate is mounted so that it may swivel or rotate in relation to the body. This enables the operator to hold the body of the device in a convenient position while testing and still maintain a vacuum seal at the foot of the device. The three centering springs return the foot to its original position upon removal from the test location. Two foot pads are also threaded into the vacuum plate. The operator can thereby apply pressure to effect a better seal by standing on the foot pads while testing on horizontal (top) surfaces. A foam rubber gasket with a 4-in (100-mm) outside diameter and a 2.75-in (70-mm) inside diameter is placed under the foot immediately prior to testing to effect a vacuum seal. Total weight of the unit as shown is 33 lb (15 kg). A photograph of the entire device is shown in Figure 4-2. The valve on the side of the unit allows the vacuum to be directed to the remote plate when testing vertical or overhead surfaces.

Figure 4-3 shows the remote vacuum head used for testing vertical and overhead surfaces. The external plate is connected to the main unit by a 0.219-in. (6-mm) inner diameter, 10-ft (3-m) long vacuum hose. The hose is connected to the plate by means of a quick-disconnect fitting. A toggle valve allows the operator to apply vacuum to the plate after the hose is pumped down. A similar fitting is mounted on the main unit. On the face of the plate is a groove into which a closed-cell foam rubber gasket can be inserted. Pressure is then applied to seal the gasket onto the test surface by pushing on the handles of the plate. The main unit is placed on a tripod support (Figure 4-4) when the remote head is being used.

Internal Components and Electronic Circuitry

The major internal components of the SAF device consist of:

- flowmeter;
- vacuum pump;
- solenoid valve;
- vacuum transducer;
- battery pack;
- elapsed time indicator; and
- digital panel meters.

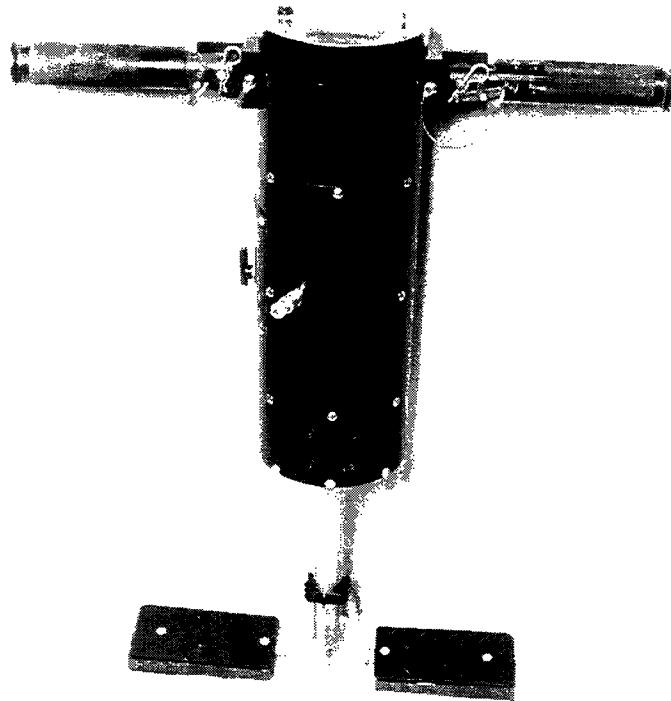


Figure 4-2. Overall view of SAF device configured for use on horizontal surfaces.

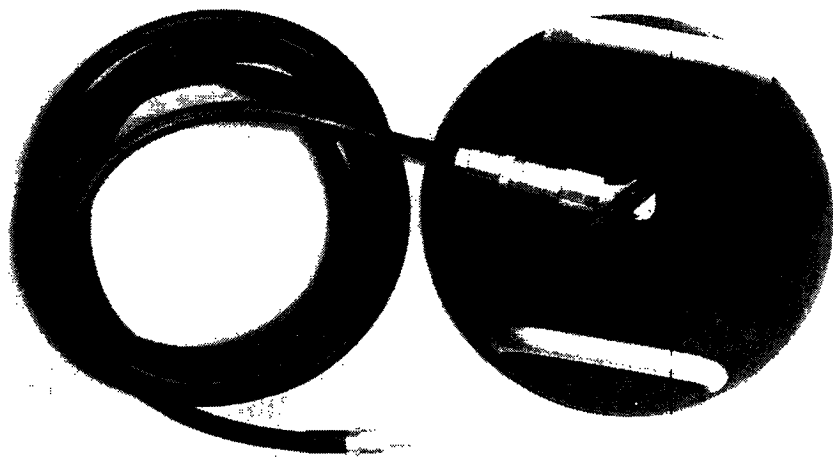


Figure 4-3. Remote vacuum head for testing vertical and overhead surfaces.



Figure 4-4. SAF device positioned on tripod support for testing of vertical surfaces.

The flowmeter is of the thermal mass flow type. This type of flowmeter is not affected by ambient conditions, can be mounted in any orientation, is small, lightweight, and highly accurate, and provides digital output. The vacuum pump is a small, lightweight, diaphragm-type pump, which operates on 12 V DC power.

The solenoid valve is a three-way valve that directs the vacuum to the directional flow valve, where the operator can select the mode of operation. The vacuum transducer verifies that the pump is working properly and that the flow readings are taken at the proper vacuum.

The battery pack consists of ten 1.2 V Ni-Cad batteries in series to provide the required 12 V, 7 Ah power source. This allows about 4 hours of continuous operation under field conditions. The recharge time is 15 to 18 hours.

The elapsed time indicator keeps track of the time that the pump runs during operation of the SAF. The digital panel meters display the flow rate and vacuum values.

Additional details on the internal components and on the electronic circuitry for the SAF are presented in Appendix A.

Operation of the Field SAF Device

The SAF device is designed to permit taking permeability readings in all orientations--horizontal surfaces (topside and overhead) as well as vertical surfaces. For overhead and vertical surfaces, the external vacuum head is used, connected to the SAF device by means of a vacuum hose. Step-by-step operational procedures for the use of the device in the field are presented in Appendix B.

5

Preliminary Testing of Field Device

Comparisons with Bench Prototype

After assembly of the field device at TRI, a series of comparison tests was undertaken on slabs previously tested for SAF using the Construction Technologies Laboratories (CTL) bench prototype. These slabs were cast from mixtures similar to those used for the developmental studies and were in the form of 12- x 12- x 3-in. (305- x 305- x 75-mm) thick slabs. Concrete mixes used to prepare the specimens are given in Table 5-1.

Concrete Mixture E was modified from the previous design to reflect very high strength (and low permeability) concretes being developed under a separate research program (28). Mixture G was added to the study to be representative of very high w/c ratio concrete, which would be expected to have a high permeability and, in effect, establish the upper limit of permeability that would be evaluated by the technique.

Slabs from Mixtures A, D, and G were maintained under wet burlap/polyethylene overnight, then transferred to heavy plastic bags for 28 days of curing. Mixture E was fully moist cured for 28 days to ensure a high level of impermeability. Mixture F was exposed to air drying immediately after demolding, in order to develop maximum curing of the latex admixture.

Table 5-1. Characteristics of concrete mixes used for comparison studies.

Mix	Quantities--lb/yd ³				Water/ Cement Ratio	Admixture	Slump (in)	Air (%)
	Cement	Sand	Gravel	Water				
A	659	1263	1772	252	0.38	---	2.3	5.0
D	374	1563	1720	224	0.60	---	2.4	6.3
E	800	1000	1800	254	0.23	Silica fume- 125 lb	9.2	1.4
F	685	1579	1311	185	0.27	Latex 25 gal	6.3	5.0
G	313	1579	1765	234	0.75	---	1.6	5.0

^aNo admixtures other than air-entraining agents used.

Note: 1 lb/yd³ = 0.59 kg/m³; 1 in. = 25.4 mm; 1 lb = 0.454 kg; 1 gal = 3.785 L.

After the conclusion of initial curing, the slabs were coated on the four edges with moisture barrier grade epoxy and placed in an environment maintained at 73 ± 3°F (23 ± 1.7°C) and 50 ± 5-percent RH for a period of 90 days. The slabs were then tested for SAF at nine positions on the face of each slab on both top (finished) and bottom (cast) surfaces using the bench prototype. The top surface of the slab cast from Mixture F could not be tested due to a very rough finish. After testing, the slabs were carefully packaged and shipped to TRI for evaluation of the field prototype. Tests were carried out approximately 4 weeks after testing using the bench prototype. Since the slabs had been in essentially an air-dry condition for many weeks prior to the first tests, one can assume that the slabs were in essentially the same state for both of the test series. Tests at TRI were carried out in an interior room maintained at 70 to 75°F (21 to 24°C). Comparative data are included in Table 5-2.

Immediately apparent are the large differences in results between the two procedures on identical slabs. There was no reason to believe, as noted above, that the permeabilities of the slabs had changed significantly between the two sets of tests. After elimination of the effects of other variables, the differences were traced to the basic operating principles of the flowmeters used. The flowmeter incorporated into the field device is an electronic mass flowmeter, which measures absolute mass flow. The flowmeter used in the bench version is a rotameter, which measures volumetric flow. The electronic flowmeter is calibrated to read in volumetric units under standard conditions and should be equivalent to the rotameter when

Table 5-2. Comparison of SAF readings for bench prototype and field unit.

SAF (ml/minute)--Top Surfaces				
Slab	Bench		Field	
	Mean	Std. Dev.	Mean	Std. Dev.
A2	48.1	4.6	11.5	3.1
D3	143.0	10.6	35.6	3.2
E5	13.4	1.9	0.5	0.2
F2	---	---	---	---
G1	142.0	34.1	26.5	2.2

SAF (ml/minute)--Bottom Surfaces				
Slab	Bench		Field	
	Mean	Std. Dev.	Mean	Std. Dev.
A2	62.0	6.0	11.9	1.3
D3	53.0	16.1	11.6	4.7
E5	8.5	2.3	0.5	0.2
F2	20.6	3.9	0.4	0.2
G1	154.0	22.6	31.8	3.5

*No reading.

both are used under standard conditions. However, all developmental testing using the rotameter had been done with the meter between the vacuum pump and the concrete test specimens. Therefore, the rotameter was operating in a partial vacuum, and not under standard conditions. However, as the test results are relative in any case, and an absolute measure of flow or permeability is not required, it was only necessary to establish that a linear relationship existed between results obtained on the same specimens using the bench and field versions of the methods. Such a relationship is shown in Figure 5-1. The

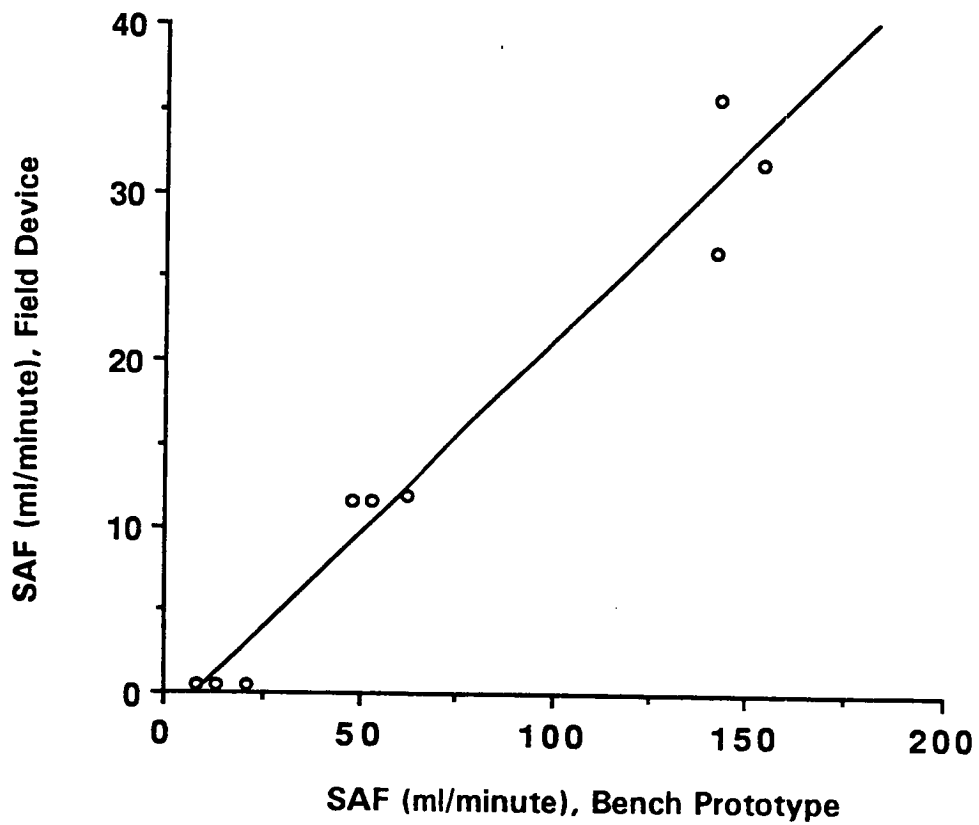


Figure 5-1. Comparison between SAF results obtained using laboratory bench prototype and field device.

correlation coefficient for the regression of the bench values on the field values was determined to be 0.963, indicating a fairly linear relationship between the two data sets. The equation of the line allowed the previous categories of SAF developed using the bench prototype to be transformed into a new set of recommendations, as follows: readings less than 5 ml/minute represent low permeability concretes, readings between 5 and 16 ml/minute represent moderately permeable concretes, and readings higher than 16 ml/minute represent highly permeable concretes.

Temperature Effects

After comparison testing had been completed at TRI, the unit was shipped to CTL for further evaluation. In order to be viable as a field device, it was deemed necessary to determine the effects of temperature, if any, on the response of the unit. For this purpose, large environmental rooms available at CTL were used. Rooms were brought to temperatures of either 38°F (3°C) or 98°F (37°C) prior to carrying out the evaluations. Slabs cast earlier in the investigation were used for these measurements. A high w/c ratio (0.6) slab from Mixture D and an LMC slab from Mixture F were used to represent a wide range of permeabilities. Slabs had been stored in the laboratory at $73 \pm 3^\circ\text{F}$ ($23 \pm 1.7^\circ\text{C}$) and 50 ± 5-percent RH for a period of approximately 22 months prior to these evaluations. Tests were first carried out at standard conditions of $73 \pm 3^\circ\text{F}$ ($23 \pm 1.7^\circ\text{C}$) at 15 positions on the cast face of each slab. After these test were completed, the slabs were moved to a room maintained at 98°F (37°C) for a period of 7 hours, and tests were repeated at this temperature. The SAF device was allowed to come to the temperature of the room for a period of 30 minutes prior to testing. After the high temperature tests were completed, the slabs were moved to a room maintained at 38°F (3°C) and allowed to equilibrate overnight. The unit was moved into the room in the morning for a period of 30 minutes, then tests were conducted.

Results are presented in Table 5-3. For these slabs, readings can be seen to be essentially independent of temperature over the range of investigation. The higher coefficients of variation associated with Slab F are reflective of the very low mean air flows encountered, and have no detrimental effect on interpretation of results. Performance of the instrument was excellent at all temperatures, and no problems were encountered.

Table 5-3. Effects of temperature on readings taken with SAF field unit.

Slab	No. Readings	Temp. (°F)	SAF (ml/minute)				
			Mean	Minutes	Max.	Std. Dev.	% C.V.
D-2	15	38	16.2	13.7	18.9	1.3	8.1
	15	73	15.3	12.7	17.8	1.5	10.1
	15	98	15.2	12.5	18.0	1.5	10.1
F-2	15	38	1.3	0.8	1.9	0.3	24.2
	15	73	1.1	0.8	1.3	0.2	17.7
	15	98	1.0	0.7	1.3	0.2	17.0

Note: °F = 1.8 x °C + 32

Testing of Outdoor Slabs

A series of outdoor test slabs cast by the Portland Cement Association (PCA) in 1979 were used for a preliminary evaluation of the unit on field-placed concrete. The slabs were originally designed to evaluate the effects of such parameters as w/c ratio, slump, air content, finishing, curing, and consolidation on deicer scaling resistance, and have been subsequently used to study the process of carbonation in concrete (29). Three slabs with a range of w/c ratios, air contents, and consolidation were selected. Three SAF tests were carried out on each slab, and 4-in. (100-mm) diameter cores were extracted from the test positions immediately after the test. The cores were then sliced to 2-in. (50-mm) thickness and dried to constant weight. The slices were then tested for air permeability using the pulse-decay technique (27). A comparison of results is shown in Table 5-4.

The tests appear to reflect the characteristics of the mixes used to cast the slabs. Lowest average results were obtained on Slab 1, which exhibited the lowest slumps and air contents. Slab 9 was intermediate, exhibiting somewhat higher slump, perhaps indicating a somewhat higher water content in spite of the reported equality in design w/c with Slab 1. Slab 11 exhibited the highest permeabilities, reflecting the higher w/c and slumps for this mix.

Table 5-4. Results of comparative tests on field slabs.

Slab	Description	Test Location	SAF (ml/minute)	Air Permeability (microdarcsies)
1	w/c = 0.43	A	6.0	45.2
	2.6-in. slump	B	3.3	19.1
	2.8% air	C	6.3	13.8
	No vibration			
9	w/c = 0.43	A	8.8	57.9
	3.8-in. slump	B	4.8	38.1
	2.8% air	C	7.5	53.2
	Internal vibration			
11	w/c = 0.50	A	13.3	91.9
	5.3-in. slump	B	13.5	118.6
	5.5% air	C	10.6	85.2
	Internal vibration			

Note: 1 in. = 25.4 mm; 1 microdarcsy = $10^{-6} \mu\text{m}^2$.

The relationship between SAF readings and actual air permeabilities for these cores is shown in Figure 5-2. There is a very strong relationship between the two test procedures. These data indicated that the SAF method could be used on actual field-cast slabs and that test results could be viewed as a good indicator of the actual permeability of the test areas. Based on these promising preliminary test results, field tests on actual structures were carried out. The field trials are described in the next chapter of this report.

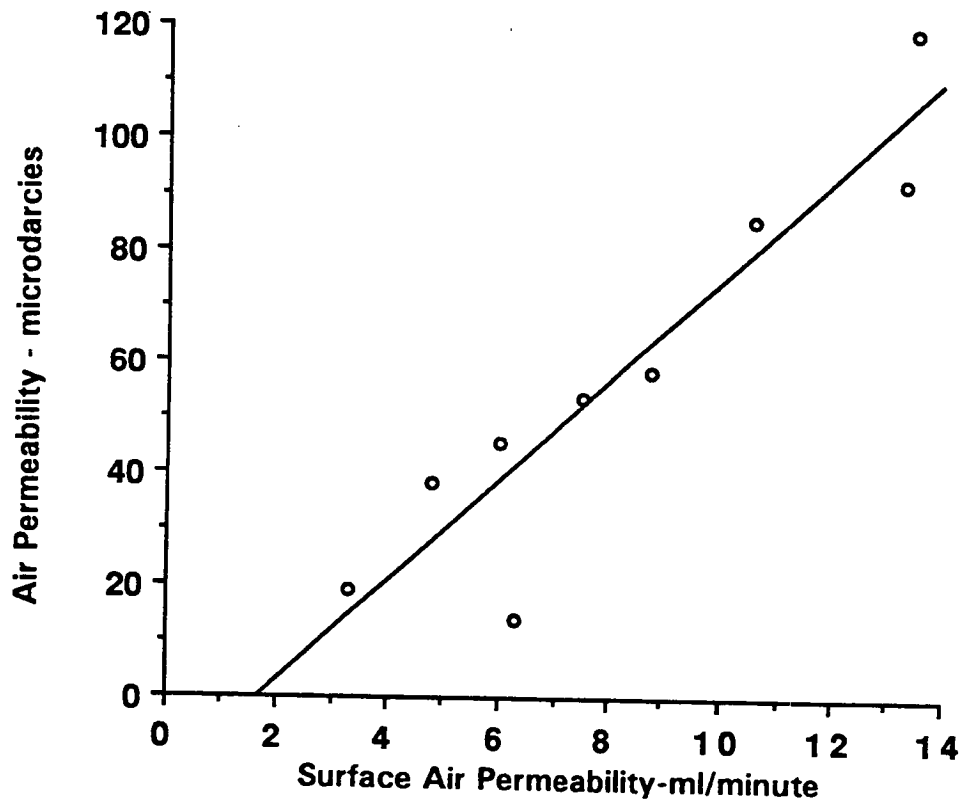


Figure 5-2. Relationship between SAF readings and actual air permeabilities for cores taken from PCA outdoor slabs.
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6

Field Trials

A series of field trials was carried out to evaluate the equipment under actual test conditions. The primary purpose of these field trials was to "shakedown" the device under a variety of conditions, make modifications (if necessary), and thereby refine the method, making it more practical and reliable. Due to the absence of convenient and standardized field techniques for assessing in situ permeability, it was not possible to make an absolute assessment of the accuracy of the procedure in the field. However, by extraction of cores from test locations and subsequent testing of these cores using standard laboratory permeability procedures, it was possible to gain some indications of the ability of the device to determine relative rankings of the permeability of field concretes. Field trials were carried out in environments representative of temperate, marine, and deicer exposures.

Field Trial No. 1--Austin, Texas

The first set of field trials was carried out on March 5 and 6, 1991, in Austin, Texas. The weather was clear and hot, with high temperatures near 95°F (35°C). The site chosen for the testing was a bridge on Route 1 (also known as Mopac highway) over Westover Road in central Austin. Testing was carried out on the 10-ft (3-m) shoulder area of the southbound passing lanes and on three of the prestressed concrete support beams in positions close to the bridge abutment. Operation of the device on the bridge deck is shown in Figure 6-1. Test results over a 36-ft (11-m) length of shoulder are given in Table 6-1.



Figure 6-1. SAF device in operation on Westover Road Bridge, on Route 1, Austin, Texas.
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Table 6-1. SAF readings taken on deck of bridge over Westover Road, Austin, Texas.

Station (ft)	SAF (ml/minute)			
	Offset (ft)			
	0	3	6	9
3	21.2 ^a	41.3	50.4	82.1
6	56.8	77.9	— ^b	40.1
9	35.3	40.3	— ^b	44.8
12	36.1	53.4	— ^b	10.0 ^a
15	32.3	57.2	79.7	59.8
18	47.3	— ^b	— ^b	44.1
21	18.3	— ^b	37.2	20.1 ^a
24	17.2	32.8	41.1	16.9 ^a
27	23.1	38.2	— ^b	30.1
30	26.4	25.8	— ^b	32.1
33	26.2	36.9	— ^b	34.8
36	26.8	24.0 ^a	— ^b	30.3
39	35.2	42.1	— ^b	29.3

^aCores removed for subsequent laboratory testing.

^bNo reading.

Note: 1 ft = 0.305 m.

Many of the results showed much higher values for flow than previously encountered in the laboratory phase, even for concretes having very high permeabilities. Much of the surface of the deck was very rough and uneven on a localized basis, which may have led to poor sealing and leaks around the gaskets. Additionally, it was noted that the rough surface caused premature wear of the gaskets. When the original gasket was replaced, much lower test readings were obtained. The need to remove traffic control, however, prevented further examination of the effects of gasket replacement on the results. Cores were taken from five locations for measurement of air permeability using the pulse decay technique.

The following day, tests were conducted on three of the prestressed support beams on the same bridge. Tests were confined to a 6-ft (3-m) section using the beams near the bridge abutment so as to allow for access to test locations from the slope without the use of special equipment. Tests were carried out on both the webs and lower flanges of the beams. Operation using the remote vacuum plate is shown in Figure 6-2. Results are given in Table 6-2.

Table 6-2. SAF readings taken on prestressed support beams of bridge over Westover Road, Austin, Texas.

Position on Beam	Distance from End of Beam (at abutment) (ft)		
	2	4	6
<u>Outside Beam--East Face</u>			
Web	19.2	12.1	18.8
Flange	14.1	8.0*	7.7
<u>Outside Beam--West Face</u>			
Web	15.9	18.3	17.2
Flange	11.3	7.0	7.9
<u>Interior Beam 1--East Face</u>			
Web	22.1	24.7	16.2*
Flange	10.3	8.3	9.2
<u>Interior Beam 1--West Face</u>			
Web	27.2	20.7	31.1*
Flange	10.9	12.2	8.3
<u>Interior Beam 2--East Face</u>			
Web	19.1	17.8	11.2*
Flange	7.3	8.1	8.8

*Cores removed for subsequent laboratory testing.
Note: 1 ft = 0.305 m.



Figure 6-2. Operation of remote vacuum plate on prestressed beams of bridge over Westover Road, Austin, Texas.

Readings were much lower than encountered the previous day on the bridge deck. It is believed that this is due to the much smoother surface on the beams, which allowed for a better seal and did not do as much damage to the gaskets. Cores were taken from three locations for subsequent laboratory testing. It should be noted that at one location on the web of interior Beam 1, the core was taken completely through the beam, allowing two test samples to be obtained from the one core. At this point in the testing it was noted that a much lower vacuum level was being achieved, even against the standard metal plate. This was indicative of battery drain, and testing was concluded at this point.

Cores were packaged and shipped back to CTL immediately after testing was concluded. Upon receipt, the top 2 in. (50 mm) of each core were removed using a water-cooled diamond saw. As noted above, for the core removed from interior Beam 1, two test samples were obtained, one from each end of the core. After cutting, the samples were placed into a forced-draft oven maintained at $140 \pm 5^{\circ}\text{F}$ ($60 \pm 3^{\circ}\text{C}$). The samples were allowed to dry to constant weight, which was achieved after approximately 3 weeks of drying. They were then placed into moisture-resistant sample containers and shipped to Core Laboratories, Dallas, Texas, where they were tested for air permeability using the pulse-decay permeameter. Results are presented in Table 6-3.

Although a general relationship between in situ and lab tests is demonstrated, as shown in Figure 6-3, the correlation is not as quantitative as in previous laboratory series. Additionally, large changes in SAF readings were not always associated with corresponding changes in laboratory values. Problems encountered during field testing, as noted above, may have been responsible for some of these discrepancies.

Field Trial No. 2--Corpus Christi, Texas

A second field trial was carried out May 7 and 8, 1991, in Corpus Christi, Texas. Weather was warm, with a high temperature of about 80°F (27°C). Intermittent rainfall was prevalent during the period. Sites included the deck of the Nueces Bay Causeway Bridge carrying Rt. 181 North from Corpus Christi and the J.F.K. Intra-Coastal Canal Bridge carrying Park Road 22 onto North Padre Island. The Nueces Bay Causeway Bridge had a recently widened deck with a 10-ft (3-m) concrete shoulder, which was available for testing. The J.F.K. Bridge had an asphalt-covered deck; however, the prestressed concrete support beams and reinforced concrete piers were available for testing. Results obtained on the Nueces Causeway deck are presented in Table 6-4.

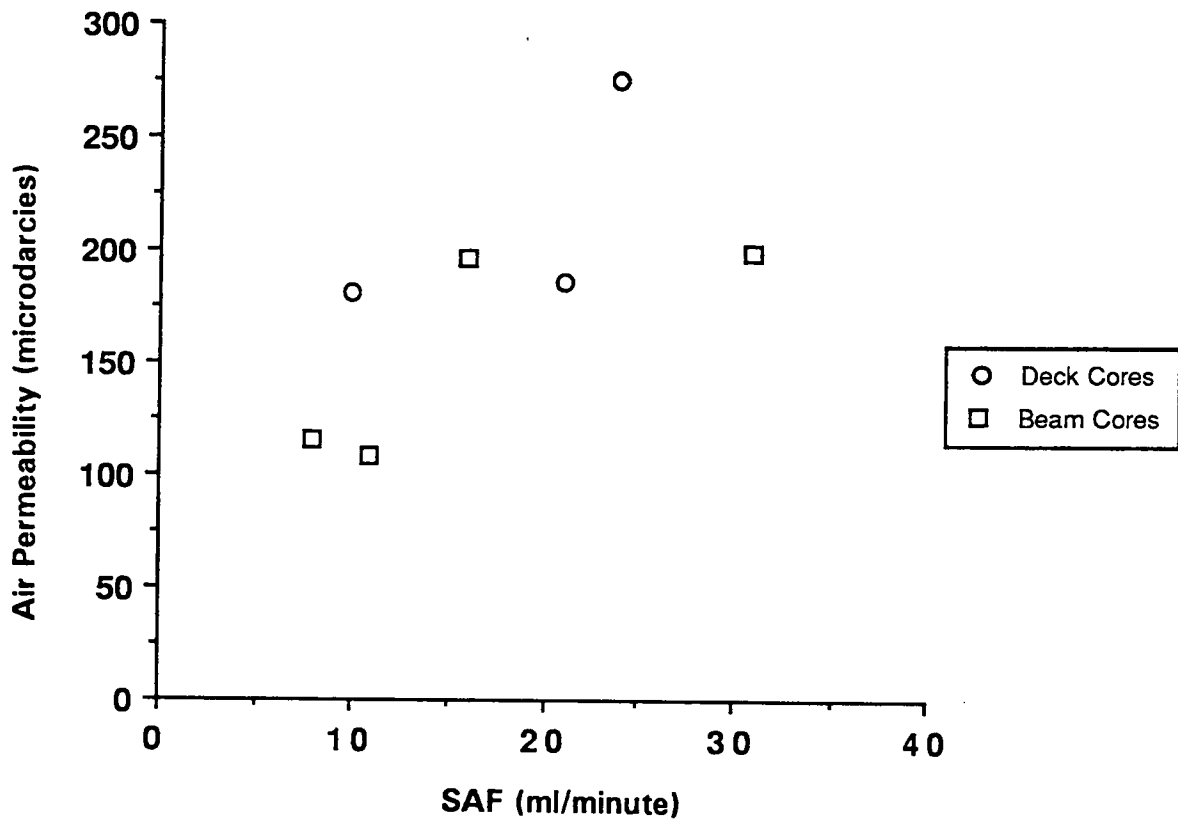


Figure 6-3. Comparison of in situ SAF and laboratory permeability testing for Austin, Texas, field site.

Table 6-3. Results of air permeability tests carried out on cores removed from bridge over Westover Road, Austin, Texas.

Core	Location ^a	SAF ^b (ml/minute)	Air Permeability ^c (microdarcies)
1-1	Deck (3-0)	21.2	186
1-2	Deck (12-9)	10.0	181
1-3	Deck (36-3)	24.0	275
1-4	Outside beam-flange	8.0	116
1-5E	Interior beam 1-web	16.2	196
1-5W	Interior beam 1-web	31.1	199
1-6E	Interior beam 2-web	11.2	108

^aLocations on deck refer to station (along length) and offset along width (in feet).

^bIn situ measurements using SAF device.

^cLaboratory measurements on cores taken from test locations.

Note: 1 ft = 0.305 m; 1 microdarcy = $10^{-6} \mu\text{m}^2$.

The readings appeared reasonable, and no problems were encountered with the equipment. Prior to initiation of this set of field trials, an alternative gasket material, which appeared to be more durable, had been obtained. In addition, it was decided to replace the gasket after every fourth reading, regardless of whether the gasket appeared worn or not. The locations closest to the curb (offset=0), however, exhibited rather high readings. This was attributed to some rough surfaces in this area, along with considerable surface cracking. After approximately 2 hours of testing, a heavy thundershower forced cessation of activities for a period of time. Immediately after the shower, cores were obtained from a number of locations on the deck that had been tested using the SAF. After coring was completed, it was necessary to remove traffic control to allow for rush-hour traffic to utilize the entire deck. No further testing was carried out at this site.

Table 6-4. SAF readings obtained on deck of Nueces Causeway Bridge in Corpus Christi, Texas.

Station (ft)	SAF (ml/minute)			
	Offset (ft)			
	0	3	6	9
0	57.2	15.0	6.5	8.4
3	37.7	14.2	18.5	25.2
6	40.6 ^a	13.8	10.5	17.0
9	35.4	7.9 ^a	10.4	13.3
12	23.0	12.3	7.5	5.0 ^a
15	20.4	8.5	16.6 ^a	13.5
18	65.2	5.3	4.8	7.7
21	20.5	6.1	5.2	6.0
24	23.4	11.1	9.4	7.1

^aCores removed for subsequent laboratory testing.

Note: 1 ft = 0.305 m

The following day, testing was carried out on one pier cap and two support beams on the J.F.K. Causeway bridge. Access to the pier cap was provided by Texas Department of Transportation personnel through a scaffolding arrangement. Results for the pier cap tests are shown in Table 6-5.

The reading at the location 6 ft (1.8 m) in from the edge and 28 in. (635 mm) up from the bottom of the cap appeared rather high. A core was taken from this location and one other on the cap for lab verification. Readings were then taken on two prestressed support beams at the north facing side of the bridge at the mainland side abutment. The beams were accessed from the abutment slope. Therefore, the greatest distance from the edge that could be reached was approximately 8 ft (2.4 m). Results are presented in Table 6-6. All readings were fairly low, indicative of good quality concrete.

Table 6-5. SAF readings taken on pier cap of J.F.K. Intra-coastal Canal Bridge, Corpus Christi, Texas.

Height from bottom of cap (in.)	SAF (ml/minute)				
	Distance from Edge of Cap (ft)				
	0	2	4	6	8
12	— ^b	8.9 ^a	15.2	9.5	14.7
28	— ^b	10.8	11.2	30.1 ^a	12.0

^aCore removed for subsequent laboratory testing.

^bNo reading.

Note: 1 ft = 0.305 m; 1 in. = 25.4 mm.

These exact same beams had been previously tested by CTL 4 years earlier as part of a Federal Highway Administration (FHWA) sponsored study on the corrosion of prestressing steel in prestressed concrete bridges. Results from that study indicated that the concrete had high quality and low permeability measured via the AASHTO T 277 technique. Chloride contents were quite low in spite of nearly 20 years of exposure to the gulf marine environment. The low SAF readings corroborate the previous observations. Cores were obtained from two positions on the beam. Since the cores were taken through the beam, a total of four test slices were obtained for subsequent laboratory air permeability testing (one slice from each end). Slices were shipped back to CTL, dried to constant weight, and shipped to Core Laboratories for air permeability testing.

Results of air permeability testing on the cores obtained from the Corpus Christi structures are given in Table 6-7. Also included are companion SAF readings obtained at core locations.

Again, as with the results for the Austin cores, there is a very general relationship between SAF reading and air permeability determined on the cores. For very low SAF values, there is a surprising degree of disparity in the measured permeabilities. SAF readings less than 5ml/minute yield air permeabilities that range from about 50 to 100 microdarcsies (5.0×10^{-5} to $1.0 \times 10^{-4} \mu\text{m}^2$). The relationship is shown graphically in Figure 6-4. As before, the results indicate that the SAF readings can be used as an indicator of relative permeability, but if quantitative data is needed, cores should be obtained and laboratory testing carried out.

Table 6-6. SAF readings taken on prestressed beams on J.F.K. Intra-coastal Canal Bridge.

Height from Bottom of Beam (in.)	Distance from End of Beam at Abutment (ft)			
	2	4	6	8
<u>Outside Beam--North Face</u>				
12	4.1	6.1	5.4	6.3
24	3.4	3.3	3.6 ^a	3.9
<u>Outside Beam--South Face</u>				
12	4.2	2.8	5.4	6.6
24	3.3	— ^b	3.6 ^a	3.4
<u>Interior Beam--North Face</u>				
12	2.8	3.4	3.5	5.1
24	2.8	2.7	2.9 ^a	3.6
<u>Interior Beam--South Face</u>				
12	3.6	7.9	3.4	4.3
24	4.6	4.8	2.3 ^a	5.1

^aCore removed for subsequent laboratory testing.

^bNot tested.

Note: 1 ft = 0.305 m; 1 in. = 25.4 mm.

Field Trial No. 3--Centre County, Pennsylvania

The final set of field trials was carried out on two bridge decks located in Centre County, Pennsylvania. The first bridge was located on Route 322 westbound out of Port Matilda, Pennsylvania, over Reese Hollow Road with bridge No. BMS 14 0322 0221 1292. The second was located on Route 220 in Julian, Pennsylvania, over Bald Eagle Creek, with bridge No. BMS 14 0220 0280 1591. All tests were carried out on the deck surfaces. Weather during the testing was cool and overcast, with high temperatures near 75°F (24°C).

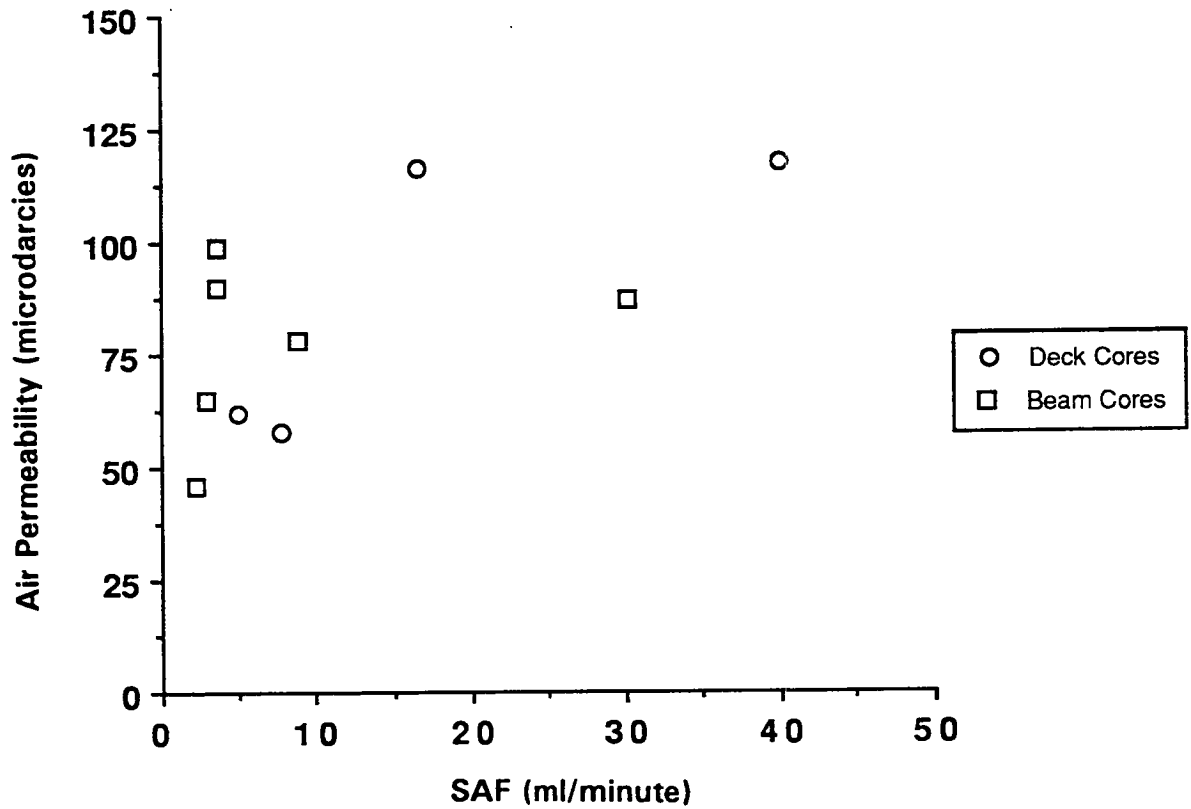


Figure 6-4. Comparison of in situ SAF and laboratory permeability testing for Corpus Christi, Texas, field sites.

Table 6-7. Results of air permeability tests carried out on cores removed from bridges at Corpus Christi, Texas.

Core	Location ^{a,b}	SAF (ml/minute) ^c	Air Permeability ^d (microdarcies)
2-1	Deck (6-0)	40.6	117
2-2	Deck (9-3)	7.9	58
2-3	Deck (12-9)	5.0	62
2-4	Deck (15-6)	16.6	116
3-1	Pier Cap (6-28)	30.1	87
3-2	Pier Cap (2-12)	8.9	78
3-3	Outside Beam--North Face	3.6	90
3-4	Outside Beam--South Face	3.6	99
3-5	Interior Beam--North Face	2.9	65
3-6	Interior Beam--South Face	2.3	46

^aLocations on deck refer to station (along length) and offset (along width), in feet.

^bLocations on cap refer to distance from edge (in feet) and height from bottom (in inches).

^cIn situ measurements using SAF device.

^dLaboratory measurements on cores taken from test locations.

Note: 1 ft = 0.305 m; 1 in. = 25.4 mm; 1 microdarcy = $10^{-6} \mu\text{m}^2$.

Testing on the Route 322 bridge deck was carried out on June 18, 1991. Initially, traffic control was set up to test along a 10-ft (3-m) shoulder on the westbound lane. However, after testing commenced, it was noted that flow readings were extremely high (over 80 ml/minute). After a brief wetting of a test area, an extensive system of microcracks in the top surface layer was detected. It was observed that the driving lane of the deck had been worn to the point that the paste-rich surface layer was no longer present, and the microcracking was much less extensive. The test area, therefore, was moved over to the driving lane in order to obtain more representative readings. Results are given in Table 6-8.

Table 6-8. SAF readings taken on deck of bridge on Route 322, Port Matilda, Pennsylvania.

Station (ft)	SAF (ml/minute)			
	Offset (ft)			
	0	3	6	9
0	9.6	22.0	10.1	2.9
3	31.3	10.8	5.3	8.0
6	13.1	9.7	12.2	32.6
9	22.2	9.7	4.0	9.3
12	38.1	13.6 ^a	9.5	9.3
15	23.3	11.7	30.0	14.0
18	33.9	3.5 ^a	6.6	26.9
21	26.6	6.7	3.2	9.4
24	13.1	14.1	3.7	26.1 ^a
27	13.9	7.0 ^a	4.2	29.1
30	10.9	8.7	16.7	22.2
33	56.0	9.8	11.7	— ^b
36	14.5	9.3	10.8	6.6
39	18.6	28.0	16.8	4.6
42	12.4	7.9	12.6	— ^b
45	21.3	8.8	— ^b	23.1
48	60.2	4.2	22.2	16.8

^aCores removed for subsequent laboratory testing.

^bNo reading.

Note: 1 ft = 0.305 m.

A considerable range of values was obtained. Some of the higher readings, for instance at locations (33-0) and (48-0), appeared to be associated with surface cracks at these test locations. A number of locations could not be tested due to surface cracking or voids in the surface at these places. All testing proceeded well for a period of about 2 hour, at which point a brief shower wet the deck and caused an interruption of testing. Since drying was slow, and more showers appeared imminent, testing was suspended, and cores were obtained for subsequent laboratory testing.

Testing on the Route 220 bridge deck was carried out the following day. Tests were carried out in the curb area of the southbound lanes, since the driving lanes had been overlaid with asphaltic concrete some years ago. For this narrow curb area the test pattern was reduced to 2 ft (0.6 m) along the length of the deck and 6 and 30 in. (152 and 762 mm) across the width of the curb. Results of the testing are shown in Table 6-9. On the whole, readings were higher than those at the Route 322 bridge deck. Four cores were selected to cover a range of values. Although some values higher than 30 ml/minute were encountered, these were, for the most part, associated with rough or cracked areas and therefore not chosen for comparison testing. After testing was completed, cores were shipped to Core Laboratories for air permeability testing.

Results of air permeability testing on the cores obtained from the Centre County structures are given in Table 6-10. Also included are companion SAF readings obtained at core locations.

Again, as in the results for the other sites, there is a general relationship between SAF readings and air permeability (see Figure 6-5). In fact, correlation for the Centre County bridges is significantly better than for the first two field sites. This may be attributable to improvements in gaskets and other aspects of the instrumentation prior to testing at the final site. Deck No. 4 is the Port Matilda Bridge and Deck No. 5 is the Julian Bridge in Figure 6-5.

Table 6-9. SAF readings taken on deck of bridge on Route 220, Julian, Pennsylvania.

Station (ft)	SAF (ml/minute) Offset (in.)	
	6	30
0	39.0	15.2
2	32.7	32.1
4	8.5	29.5
6	37.3	37.9
8	46.2	17.4
10	21.5	30.8
12	21.0	23.5
14	28.0	53.0
16	8.4 ^a	16.6
18	18.9	29.4
20	9.1	26.0
22	14.5 ^a	19.4
24	8.9	13.1
26	29.2 ^a	34.0
28	23.8	51.4
30	19.5	62.3
32	7.6 ^a	49.2
34	10.5	31.5
36	10.8	19.1
38	15.0	22.0
40	33.2	--- ^b

^aCores removed for subsequent laboratory testing.

^bNo reading.

Note: 1 ft = 0.305 m; 1 in. = 25.4 mm.

Table 6-10. Results of air permeability tests carried out on cores removed from bridges in Centre County, Pennsylvania.

Core	Location ^{a,b}	SAF ^c (ml/minute)	Air Permeability ^d (microdarcies)
4-1	Deck (27-3)	7.0	52
4-2	Deck (18-3)	3.5	71
4-3	Deck (12-3)	13.6	113
4-4	Deck (24-9)	26.1	233
5-1	Curb (16-6)	8.4	109
5-2	Curb (22-6)	14.5	159
5-3	Curb (26-6)	29.2	204
5-4	Curb (32-6)	7.6	109

^aLocations on deck refer to station (along length) and offset (along width), in feet.

^bLocations on curb refer to station (along length), in feet, and offset (along width), in inches.

^cIn situ measurements using SAF device.

^dLaboratory measurements on cores taken from test locations.

Note: 1 ft = 0.305 m; 1 in. = 25.4 mm; 1 microdarcy = $10^{-6} \mu\text{m}^2$.

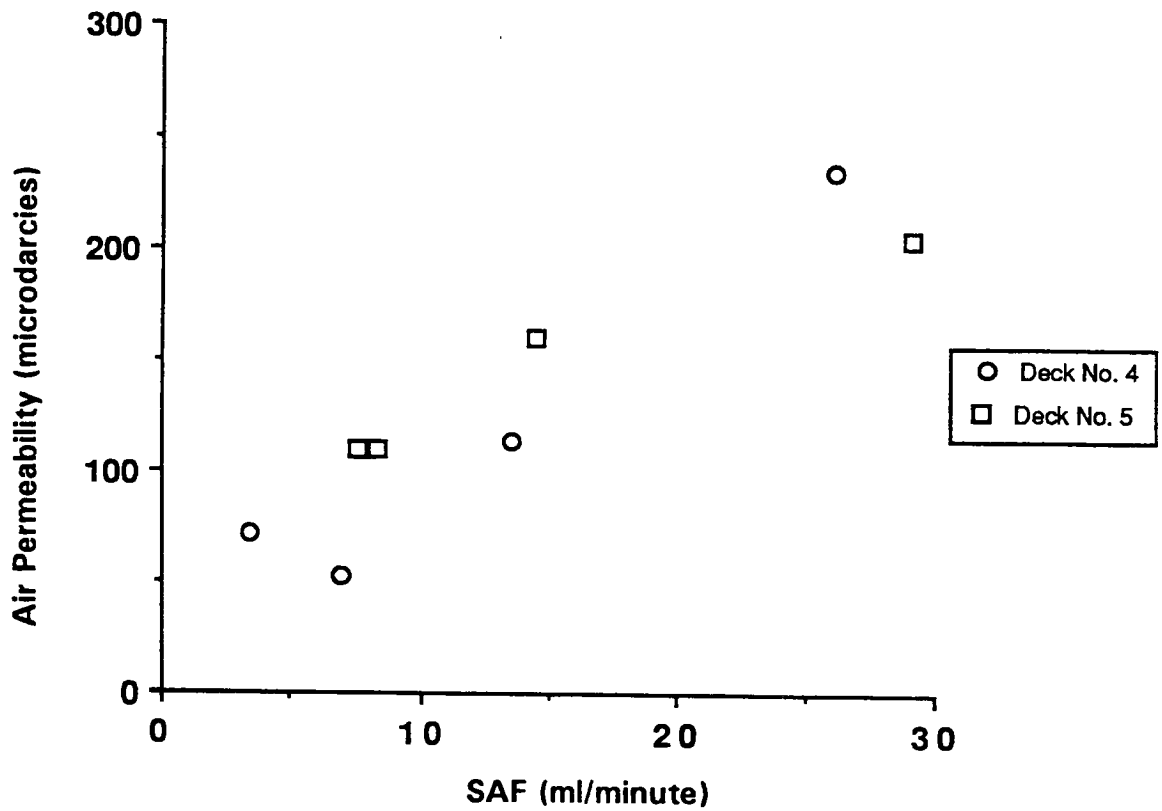


Figure 6-5. Comparison of in situ SAF and laboratory permeability testing for Centre County, Pennsylvania, field sites.

7

Summary and Recommendations

Summary of Test Method

The method developed under this research program can be used to gain an indication of the relative permeability of concretes both in the laboratory and on actual field structures. The method is based on measurement of the rate of air flow through a vacuum plate placed on a concrete surface under a vacuum of approximately 25 in. of mercury (16.6 kPa absolute pressure). The effective depth of measurement is demonstrated to be approximately 0.5 in. (12 mm) below the surface. Two versions of the technique, a laboratory prototype and a portable field device, were developed. The laboratory device uses bench components and a rotameter for measurement of air flow. Flows lower than about 30 ml/minute are generally associated with low permeability concretes. Flows exceeding 80 ml/minute are indicative of high permeability concretes. For calibration of the method, concretes were cast using a variety of w/c 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.

The field device is self-contained within a 33-lb (15-kg) package. The unit is powered by Ni-Cad rechargeable batteries and can operate continuously for approximately 4 hours on a single charge. Measurements on horizontal surfaces are carried out by placing the unit on a closed-cell foam gasket placed on the desired test location. The operator stands on two "feet" attached to the unit while running the test. On vertical surfaces, a remote vacuum plate containing an affixed closed-cell foam gasket is placed against the surface to be tested and is linked to the unit through a 10-ft (3-m) vacuum hose. Since the flow path and type of

flowmeter utilized in the field device differs from that used in the bench version, interpretation of results is somewhat different. Values less than 5 ml/minute are associated with low permeability concretes. Highly permeable concretes generally exhibit flow values greater than 16 ml/minute when tested using the field device.

A recommended test procedure, in American Society of Testing and Materials (ASTM) format, has been prepared for the SAF method of evaluating the permeability of concrete. It is presented in Volume 8, "Procedure Manual," of this report.

Applicability of Test Method

The method has been shown to be applicable under both laboratory and field conditions. It has shown good correlation with standard techniques when applied to carefully prepared concrete specimens cast under controlled laboratory conditions. In the laboratory, the method may be used to gain an indication of the relative permeability of various concrete mixtures and therefore can be used for such activities as materials development, research activities, and product screening.

The major advantage of the new method is that it can be used under field conditions on in-place concrete structures. The equipment is portable and fairly simple to operate. A large number of readings can be obtained in a short period of time. Potential applications of the device could include such activities as:

- Determination of relative permeability of concrete during rehabilitation surveys;
- Verification that low permeability has been established for special concrete overlays;
and
- Establishing general quality of concrete in routine construction or in cases where questions have arisen.

While there are some limitations (see next section), the method has been used on a variety of structures under differing climatic conditions with overall good success.

Limitations of Test Method

Field testing introduces a variety of largely uncontrollable variables. The method requires an initially dry surface. Therefore the testing cannot be carried out under wet conditions. Additionally, the technique will be influenced by internal concrete moisture content, even if the surface is dry. If testing is to be carried out on a surface that has recently been wetted, it may be necessary to pre-dry the test areas prior to initiation of testing. If this is not practical, then one should wait at least 24 hours after cessation of rainfall before conducting the tests.

Surface features apparently have an influence on the test results. However, it was not possible to study the myriad of concrete surface characteristics within the scope of this development project. Some general guidelines would include the avoidance of rough or grooved surfaces or surfaces that are extremely weathered and weak. Additionally, surface microcracking can lead to anomalously high results, and such surfaces should also be avoided. In many cases, it is possible to ascertain whether a test result is valid by comparing the vacuum obtained during the test to that obtained on the standard metal plate. If the two readings differ by more than 5 mm of Hg (0.6 kPa), then an inappropriate test surface is indicated.

Other variables, such as the presence of reinforcing steel or ambient temperature, do not appear to have a significant influence on the test results. It is wise to avoid areas directly above steel with cover less than 0.5 in. (12 mm). Additionally, while temperature, per se, does not influence the test, the electronic components are not designed for continuous operations below 32°F (0°C) or above about 120°F (50°C).

Recommendations

It is recommended that further evaluations of the method be carried out to more precisely determine the effects of concrete surface characteristics on the test. This could include surfaces having various degrees of roughness as well as scaled and microcracked surfaces. Gasket materials that conform more closely and also adhere to the surface being tested, thereby allowing testing of rougher surfaces, would also be desirable.

Appendix A

Internal Components and Electronic Circuitry

Internal Components

The major internal components consist of a thermal mass flowmeter, a 3-way solenoid valve, a DC-operated miniature vacuum pump, a vacuum transducer, a Ni-Cad rechargeable battery pack, an elapsed time indicator, and two digital panel meters. Also included are associated electronics for powering the instrument and scaling the output signals from the transducer and flowmeter. All of the components are mounted on a module that can be easily installed or removed from the main housing (see Figure A-1). A brief description of each major component follows.

Flowmeter

A Teledyne-Hastings-Raydist thermal mass flowmeter Model HFM-200L was used. This instrument measures the flow rate of air, in standard cubic centimeters per minute (sccm), from the concrete. For the purposes of this method, this is equivalent to ml/minute. The mass flowmeter contains a heated tube instrumented with thermal sensors on each end. As a gas flows through the tube, it extracts heat and creates a temperature difference along the length of the tube. This temperature difference is proportional to the time rate of mass flow and is scaled to a linear output at standard conditions of 0°C and 760 mm Hg (101 kPa) absolute pressure by electronics within the meter. This type of flowmeter has several

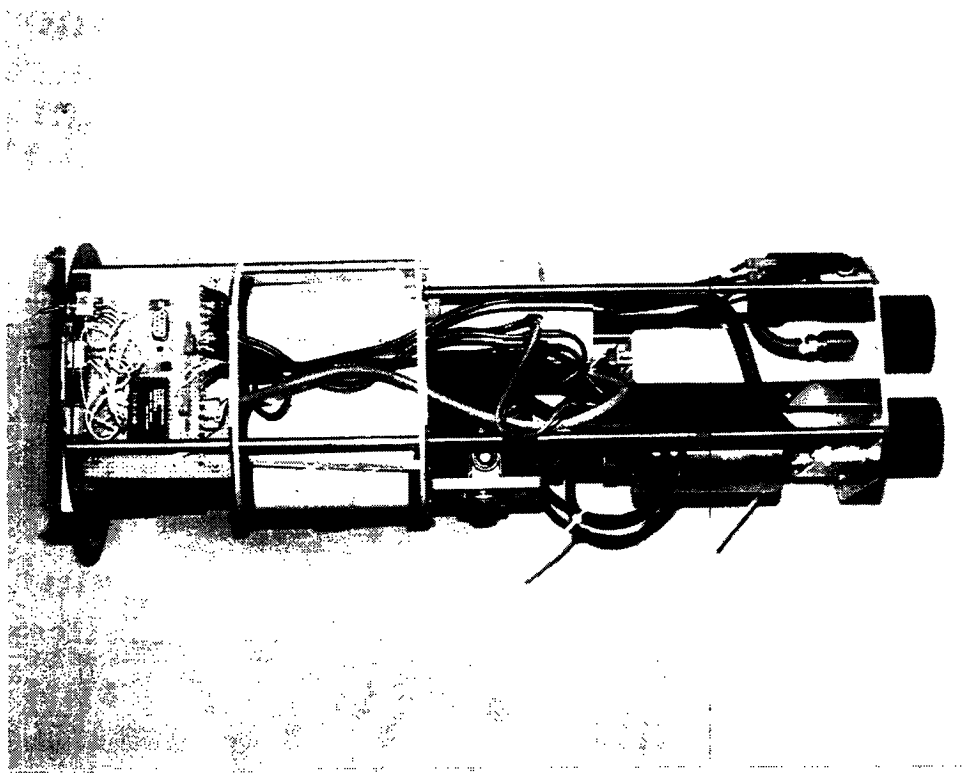


Figure A-1. Instrument module removed from housing of SAF device.

advantages over other types of meters (which measure volumetric flow directly). Deviations from standard conditions will not affect the output of the reading. Additionally, an electrical analog signal of 0- to 5-V DC can be displayed on a digital panel meter. The flowmeter can be mounted in any orientation and weighs only 1.8 lb (0.8 kg). Accuracy is ± 1 -percent full-scale and repeatability is ± 0.2 -percent full-scale.

Vacuum Pump

A K-N-F Neuberger, Inc. Model UN79 MNI diaphragm vacuum pump was chosen since it duplicated the pump used in the laboratory development phase of the project, yet is capable of operation under DC battery power. It is a 12-V DC pump that is capable of pulling down to 635 mm Hg vacuum (16.6 kPa absolute pressure) or better at zero throughput. It is relatively small and light (2.0 lb [0.9 kg]) and draws 1.5 A.

Solenoid Valve

A Humphrey Products, Mini-Mizer Model 3E1 three-way, 12-V DC solenoid valve is used. When energized, the valve directs the vacuum to the directional flow valve, where the operator can then select the mode of operation (i.e., horizontal or vertical). The flow reading can then be obtained. When non-energized, the vacuum is vented to the atmosphere so that the unit may be moved to another location.

Vacuum Transducer

The transducer is a SENSOTEC Model V/6689-01, and it verifies that the pump is working properly and that flow readings are taken at the proper vacuum. It has good accuracy (± 0.25 -percent full-scale) and a linear 0- to 5-V DC output that is easily scaled and displayed.

Battery Pack

Ten "F" size Ni-Cad cells are connected in series to provide a 12-V, 7-Ah battery pack. Ni-Cad batteries were chosen because of their high energy-to-weight ratio. Considering the drain of the vacuum pump, solenoid, and associated electronics, this allows for approximately 4 hours of continuous operation under field conditions. Longer working times

could have been achieved by using larger batteries or a remote battery pack, but both of these were felt to be undesirable in light of the criteria for portability and light weight discussed above. The batteries must be charged overnight on the day prior to testing. A recharge time of 15 to 18 hours is recommended.

Elapsed Time Indicator

A SYRELEC Model 6108-4S elapsed time indicator indicates elapsed time in seconds. It is activated when the vacuum pump switch is turned on and stops timing when the switch is turned off. A separate switch resets the indicator to zero. It is powered by an internal lithium cell.

Digital Panel Meters

Two ACCULEX Model DP-2000 digital voltmeters were chosen to display flow and vacuum values. These are miniature 4-1/2 digit meters with liquid crystal display for viewing in direct sunlight. They have an accuracy of ± 0.06 -percent full-scale, a movable decimal point, and a "hold reading" capability.

Electronic Circuitry

The general electronic component diagram of the device is shown in Figure A-2. The circuitry may be viewed as two connected modules, the vacuum pump module and the readout module. These are both housed in the main unit.

The pump module is powered by the rechargeable Ni-Cad battery pack. The battery pack consists of ten 1.2-V Ni-Cad batteries in series. A total of 12 V are required to power the vacuum pump and the timer. The pack is located in the instrument module between the electronic circuitry and the vacuum pump. It is separated from the electronics by a 0.125-in. (3-mm) neoprene gasket. The battery pack may be recharged through the battery charger jack located on the panel. The pump switch is located on the instrument panel and activates both the vacuum pump and the timer. With power to the pump, the pressure is sensed by the in-line vacuum transducer. This pressure is then converted to an electrical signal, which is then output to the voltage divider and vacuum readout, respectively. At the same time, the timer clocks the elapsed time of the pump run. The elapsed time of the pump, while running, is displayed by a digital readout on the panel (see Figure A-3). It is

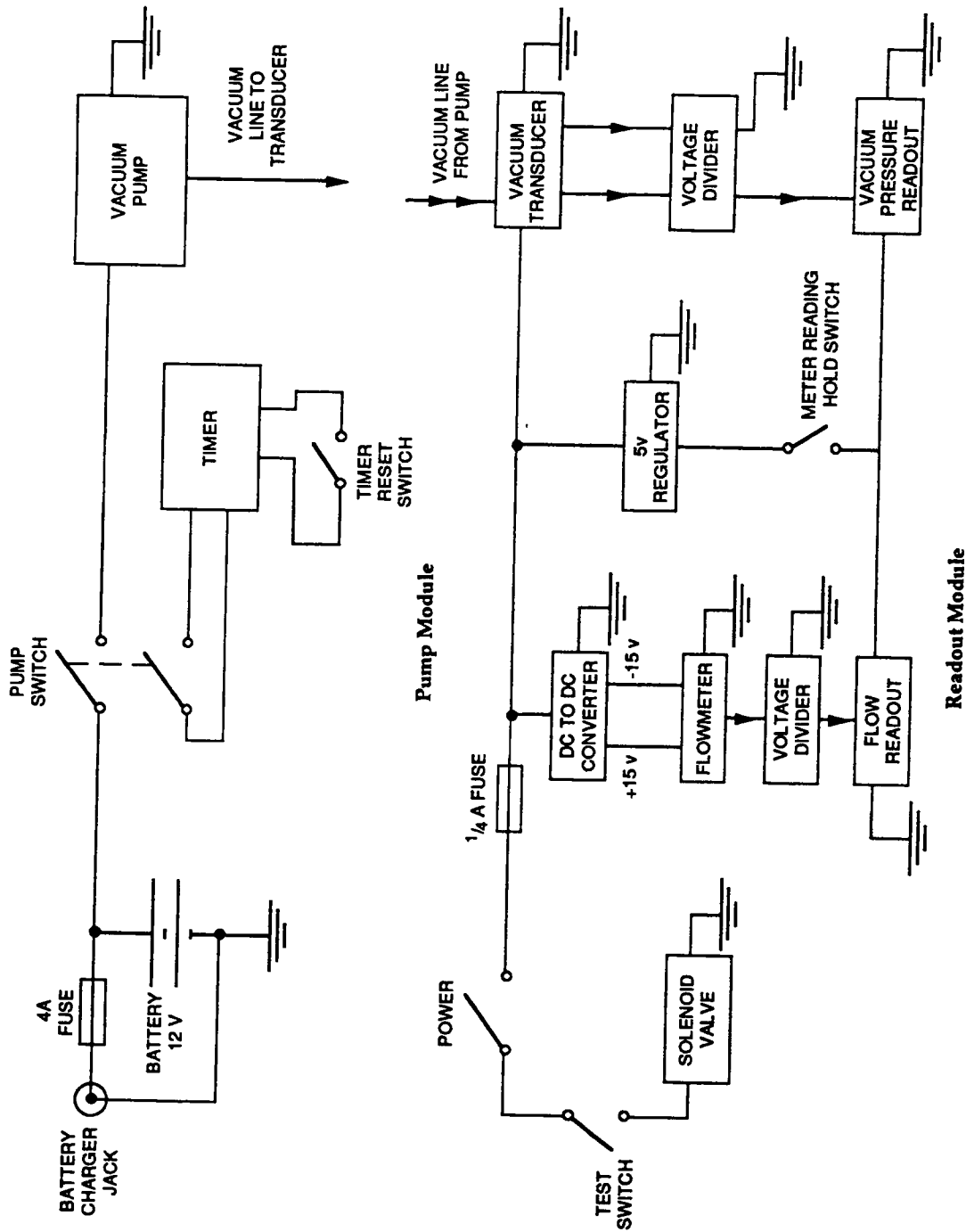


Figure A-2. General electronic component diagram.

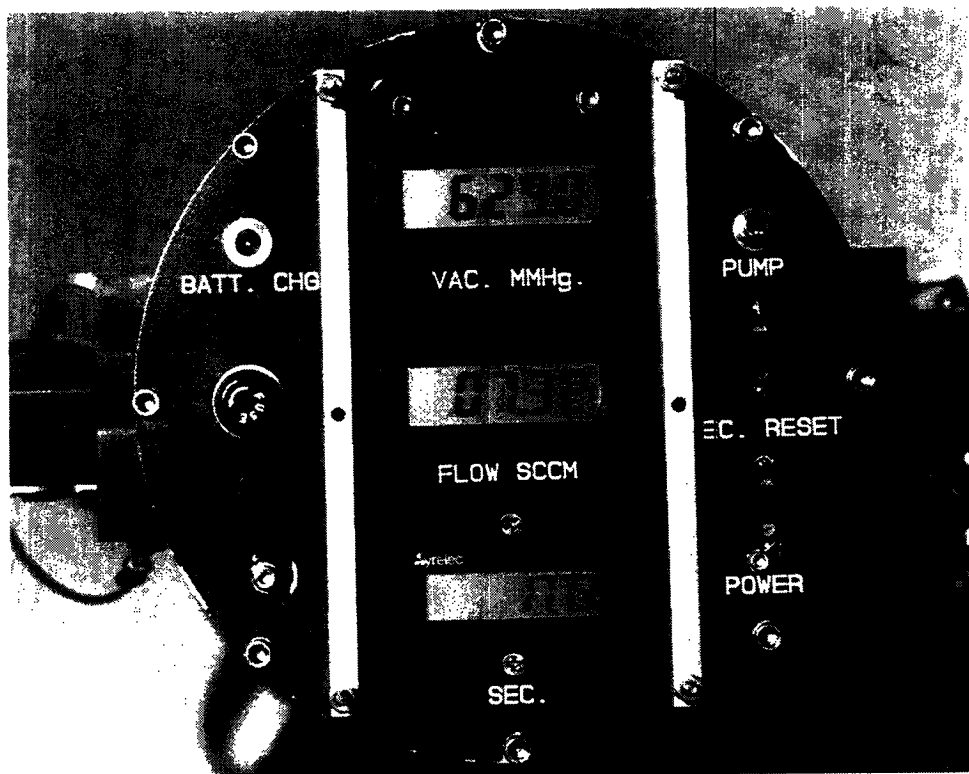


Figure A-3. Instrument panel showing digital readout gages for vacuum, flow, and elapsed time.
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accurate to within 0.01 seconds and may be reset at any time by flipping the reset switch on the panel.

The readout module is powered by the output of the vacuum transducer, which drives four devices: a 5-V regulator for the use of the readout circuit, the solenoid valve, a DC to DC converter, which powers the flowmeter, and the vacuum pressure readout. Both the flowmeter and the pressure readings can be captured by pushing the "hold" switch located on the right handle. The power switch, located on the panel, turns the readout module on and off. With power on and the vacuum pump running, the vacuum transducer senses pressure and converts that pressure to an electrical signal. The signal is between 0 and 5 V. The output is positive for vacuum and negative for pressure above zero gage.

The DC to DC converter provides power to the flowmeter. The converter accepts the voltage output of the vacuum transducer and creates two low-current voltage references, + 15 V and -15 V, required for operation of the flowmeter. With the power from the DC to DC converter the flowmeter can measure up to 300 ml/minute of air flow. An output signal of 0 to 5 V can be delivered at approximately 5 ma to the voltage divider.

The voltage divider accepts the outputs of the flowmeter and the vacuum transducer and transforms their outputs to 0 to 0.3 V and 0 to 0.76 V, respectively. The panel meters receive the output voltages from the dividers and a 5-V regulator. The regulator accepts the voltage output of the transducer and produces a low current 5-V reference for the meter readouts.

Appendix B

Operational Procedures for the Use of the SAF Device in the Field

Horizontal Flat Surfaces

1. Remove instrument from its case and install the two foot pads. The foot pads should be screwed all the way into the tapped holes on the suction foot base and then backed out until the aluminum checkered plates are pointed to the top of the machine.
2. Unfold the two handles by pushing the buttons on the end of the "T" handle lock pins and removing them. When the handles are horizontal, the lock pins need to be reinserted through other holes in the handle brackets to lock the handles in the extended position.
3. Make sure that both switches in the right handle are in the "off" position (toward the end of the handle). If the elapsed time indicator is not set to zero, do so at this time with the **SEC. RESET** switch. Return the **SEC. RESET** switch to the "off" position. Ensure that the directional valve is in the "down" position pointing towards the feet of the instrument.
4. Turn on the **POWER** switch and observe that the digital panel meters are activated. Wait 10 minutes for the instrumentation to warm up and stabilize. There are three digits to the left-hand side of the decimal point on the vacuum

meter and two digits on the left-hand side of the decimal point on the flowmeter. These should read zero. The digits to the right-hand side of the decimal point on both meters are insignificant and should be disregarded. A minus sign also may be seen to flicker off and on at the left-hand side of the meters. Pay no attention to this sign. If the flow and vacuum meters seem to be displaying correctly, the next step is to check operation on a reference plate. This should be done at the beginning of the working day or whenever readings are questionable.

5. Place a pre-formed closed-cell foam rubber gasket on an impermeable metallic reference plate. Center the suction foot over the gasket.
6. Stand on the foot pads with the balls of the feet. About one-half body weight should be placed on the foot pads and the other half should be supported by the heels. This action will compress the rubber seal against the test spot.
7. Turn on the **PUMP** with the switch on the panel. You will notice that both the flow and vacuum gages will display values, and the elapsed time indicator will start. The vacuum should quickly stabilize between 615 and 635 mm Hg, vacuum. The flow will have a high initial value due to air in the lines, but will start to stabilize after about 15 to 20 seconds.
8. Next, push the uppermost switch on the right handle toward the main body with the thumb. This opens the solenoid valve to the suction foot.
9. When the elapsed time meter reads 45 seconds, slide the lower switch on the right handle toward the main body. This will "hold" the readings on the digital meters. Record the flow reading at this point. The vacuum should read between 615 and 635 mm Hg, and flow should be less than 1 sccm (1 ml/minute).
10. Turn off the vacuum **PUMP** and the solenoid valve. Reset the hold reading switch on the right handle and the **SEC. RESET** switch on the panel. The device is now ready to be moved to the test spot.
11. Tests on actual concrete surfaces are performed in a manner identical to the initial check test. In some cases, however, it may take longer than 45 seconds for the readings to stabilize. Surfaces should be dry, free of dirt or debris, and not cracked, grooved, or textured.

Vertical and Overhead Surfaces

1. Operation of the permeameter on vertical and overhead surfaces is accomplished with the use of the remote vacuum plate.
2. To support the system during testing, place the main unit in the tripod.
3. Turn the directional valve to the "up" position pointing in the direction of the panel. This will direct the vacuum to the remote plate.
4. Make sure that both switches in the right handle are in the "off" and "release" positions (toward the end of the handle). If the elapsed time indicator is not set to zero, do so at this time with the **SEC. RESET** switch. Return the **SEC. RESET** switch to the "off" position.
5. Turn on the **POWER** switch and observe that the digital panel meters are activated. Wait 10 minutes for the instrumentation to warm up and stabilize. There are three digits to the left-hand side of the decimal point on the vacuum meter and two digits on the left-hand side of the decimal point on the flowmeter. These should read zero. The digits to the right-hand side of the decimal point on both meters are insignificant and should be disregarded. A minus sign may also be seen to flicker off and on at the left-hand side of the meters. Pay no attention to this sign. If the flow and vacuum meters seem to be displaying correctly, the next step is to check operation on a reference plate. This should be done at the beginning of the working day or whenever readings are questionable.
6. Place the remote vacuum plate on the test location by pushing against the handles with both hands. This will insure a good seal on the foam rubber gasket. Open the toggle valve by using the thumb to flip the toggle into the "up" position.
7. Turn on the **PUMP** with the switch on the panel. You will notice that both the flow and vacuum gages will display values, and the elapsed time indicator will start. The vacuum should quickly stabilize between 615 and 635 mm Hg, vacuum. The flow will have a high initial value due to air in the lines, but will start to stabilize after about 15 to 20 seconds.
8. Next, push the uppermost switch on the right handle toward the main body with the thumb. This opens the solenoid valve to the remote plate.

9. The flow reading will take somewhat longer to stabilize than when the unit is being used on horizontal surfaces. As a guide, allow at least 1 minute for stabilization of the reading.
10. Next, slide the lower switch on the right handle toward the main body. This will "hold" the readings on the digital meters. Record the flow reading at this point.
11. Turn off the vacuum **PUMP** and the solenoid valve. Reset the hold reading switch and the **SEC. RESET** switch. The remote head is now ready to be released from the concrete surface.
12. Remove the remote head by disconnecting the quick-disconnect fitting on the permeameter. This will release the vacuum and enable the removal of the remote head.

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