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Predicting Concrete Durability from its Absorption

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Synopsis : This paper discusses the current approach for specifying the durability of concrete in structures. The shortcomings of the use of bulk parameters such as strength, water/binder ratio and binder content to specify durability are discussed. Studies carried out over the last 10 years at Dundee University, using simple permeation tests, which are sensitive to curing, cement type and grade of concrete, have shown close association between permeation properties and the durability of concrete.

This paper deals with the measurement of concrete durability by the Dundee-modified Initial Surface Absorption Test (ISAT). A wide range of concrete mixes made with ordinary portland cement and blends with pulverized-fuel ash (PFA) and ground-granulated blastfurnace slag were designed. The duration of moist curing was varied from 0 to 28 days, and the maximum aggregate size from 5 to 40mm. All mixes were tested for absorptivity and aspects of durability including freeze/thaw resistance, carbonation, chloride ingress and mechanical wear.

The results show that the absorptivity of concrete, measured with the ISAT, could be used as an accurate specification for concrete durability, irrespective of curing, grade or mix constituents.

A tentative surface absorptivity classification for durability has been proposed.

Keywords: Abrasion; absorption; carbonation; chlorides; curing; diffusion; durability; freeze thaw durability; permeability; structural design; tests

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INTRODUCTION

Concrete technology and construction, barring a few notable innovations such as reinforced concrete in 1917(1) and prestressed concrete in 1933(2), have evolved rather slowly. For a long time, concrete has been considered as a bulk material that can be specified satisfactorily in terms of workability and strength alone and, unfortunately, this remains the typical position today. Any attempt to change this perception of concrete is resisted strongly on the grounds that strength relates broadly with all other properties and is an adequate measure of durability.

Notwithstanding this general association, the role of strength as a concrete durability indicator has been questioned. Indeed, experience has forced most national Codes of Practice for concrete structures to attempt to specify various required concrete characteristics for the range of exposure classes. However, there is little acknowledgement of the fact that concrete quality in a structural element varies across the section due to migration and settlement of water and aggregates respectively, as well as the relative humidity and temperature conditions of the surrounding environment(3). Such effects produce concrete with the weakest layers nearest to the surface, making the protective layer of concrete cover to steel reinforcement the most vulnerable, particularly when subjected to poor curing. Furthermore, many important durability problems, such as chloride ingress, carbonation, corrosion and sulphate attack can be significantly affected by the chemistry of the cement used, as well as the physical structure of the hydrated cement paste.

Fortunately for concrete construction, economic constraints worldwide are making designers more accountable for costing structures in terms whole-life performance. There is already a move in this direction(4), and it is of note that some national government authorities are now considering the whole-life costs of concrete structures as an essential part of the design process. This, and the lessons learnt from the rising costs of repair and maintenance of concrete structures(5), are making engineers move towards directly designing concrete for durability. Whilst this is clearly the way forward, the question of how best to realise this in practise remains to be resolved and is giving rise to some serious debate.

SPECIFYING FOR DURABLE CONCRETE

Conventional Specifications

It could be argued that even in present times, engineers are designing durable structures through passive specifications which imply, rather than directly specify, concrete durability. Moreover, engineers often don't know how long their designed structures will last. Most specifications for concrete can be divided into two separate but closely related phases. Firstly, a set of construction and structural requirements, namely the necessary workability and strength. Secondly, the designer will turn his attention to durability and is immediately faced with two major unanswered questions,

(i) *No serviceable life is stated by the client.*

(ii) *Little detail is known about effects of the exposure environment on service life.*

The dilemma then faced is to provide a satisfactory structure whilst fulfilling only vague requirements for durability. The designer will inevitably turn to his experience and the recommendations of Codes of Practice. It is not possible to provide any answer to the first of these problems but it seems likely that lifespans in excess of 100 years may be required for structures in the most aggressive environments such as highway and marine sites. The recommendations of Codes of Practice internationally are remarkably similar in their approach, even if some details differ. Typically specified parameters are,

- *Binder type, minimum binder content and maximum water/binder ratio*
- *Minimum strength grade, cover depth and degree of compaction*
- *'Adequate' curing for a fixed period of time*

This route to producing a 'durable concrete' is not incorrect, but is incomplete. Attention to detail goes a long way to improve the risk of premature deterioration as the good concreting practice of the CEB(6) illustrates. It is quite clear that concrete has to be designed and produced correctly to achieve a required durable life(7), and in an ideal world no further action would be necessary. However, such an approach is not a panacea for excellence(5), as the UK's annual £20 billion repair and maintenance costs for concrete structures(8) shows, and there must be some method of quality control testing to ensure that an acceptable standard is met.

Active Specification for Durability

Deliberate and additional specification strategies are, therefore, necessary for concrete to be designed for durability. Recognition must be made that the relative performance of commonly used binders such as the various portland cements, pulverized-fuel ash (PFA) and ground granulated blastfurnace slag (GGBS) varies with different exposure environments, and that specification by the 'conventional' criteria alone is not adequate. For example, PFA concrete can be as much as 5 times more resistant to the ingress of chlorides than equal design strength OPC concrete(9).

A 'complete' concrete specification would need to provide a balanced set of concrete characteristics which takes into account all the requirements for construction (such as workability), structural capacity (strength and dead load) and durability (cover to steel, permeation properties and chemical resistance), as illustrated in Figure 1.

To specify durability by performance characteristics there are three requirements:

(i) A suitable durability measure for specification and compliance purposes.

(ii) A simple and reliable test.

(iii) A test method that is suitable for site use.

Clearly, direct testing of durability would be most desirable, but no such tests have been developed so far. Even accelerated durability tests, which are sensitive to the effects of curing history, strength grade, and cement type could not practically meet the above criteria, since they are limited to laboratory use, and are time consuming and costly. On the other hand the links between permeation properties and durability have long been recognised(10), and it has been suggested(11) that permeation tests, which respond to the microstructural make-up of concrete, point to a way forward in specifying concrete by performance-related criteria. Some of these tests have so far been developed for site use; however, at present their use is limited.

CONCRETE QUALITY FROM PERMEATION

Variations in the make up of concrete arise not only from the inhomogeneity of constituent materials, but also result from bleeding and segregation in the vertical plane. There is an increase in quality with depth from surfaces exposed to the atmosphere(12), Figure 2, as a result of the differential rate of moisture loss, which becomes acute on site if proper attention is not paid to curing. The result of these combined effects is a layering effect, which has three basic elements,

(i) *A surface 'skin', a few millimetres deep, composed mainly of weak mortar.*

(ii) *An intermediate layer over which the concrete quality improves to a maximum.*

(iii) *A bulk region, of relatively constant quality.*

The relative depths of these layers can vary with curing and concrete grade(3), but the significance of this layering effect is that the cover region, which protects the reinforcing steel from the ingress of aggressive environmental agents, such as chlorides and carbon dioxide, is of lower quality than that of the bulk.

Whilst there are many in situ test methods, such as Schmidt hammer, pull-out test and ultrasonic pulse velocity, these tend to be strength-related and are more sensitive to overall bulk concrete quality than to the condition of the cover concrete.

The relationships between the durability aspects of concrete and its resistance to the ingress of aggressive gases and fluids(9), give rise to a serious possibility for both checking compliance with performance specification in-situ, and estimation of the expected life of concrete in different exposure environments. .

Depending upon the prevailing conditions, the movement of aggressive fluids and ions may be driven by one, or a combination of up to three basic mechanisms. These are,

Absorption-	*liquid movement caused by capillary pore suction*
Permeability-	*fluid movement under the action of a pressure gradient*
Diffusion-	*ionic movement under the action of a concentration gradient*

These properties are collectively defined as the permeation properties(11). A number of permeation tests with in-situ application exist which can measure individual permeation properties of concrete. These tests can be used to provide necessary links between concrete design and potential durability by introducing information about the response of the pore system to fluids and ions as shown in

Figure 3. This can only improve the specification of concrete for durability. Furthermore, the variation in concrete durability arising from materials, w/c, type of element, workmanship, curing, cover, and exposure can be measured in situ, using permeation tests, which give a single-parameter assessment of concrete quality (Figure 4).

This study has correlated the results of accelerated durability tests with those of the Initial Surface Absorption Test (ISAT). The test is practically suited for in-situ work, being portable, cheap and sensitive to small changes in mixture constituents, concrete grade, and curing(14), and also has a UK National Standard(15). The ISAT measures the absorptivity of the surface and near-surface layers of concrete, which are generally of the poorest quality, thus giving a worst-case assessment of concrete durability.

INITIAL SURFACE ABSORPTION TEST (ISAT)

The ISAT apparatus (Figure 5) whilst adopting the general principles of the British Standards(15,16), was modified to make it more accurate and easier to use(11). A cap of known area is clamped to the test surface, with one vertical branch acting as a reservoir, which can be isolated by a tap. Another branch is connected to a calibrated capillary tube, which measures the rate of absorption of water into the concrete below the cap on closure of the tap.

It is recommended that ISAT measurements should be taken at 10, 30, 60 and 120 minutes after the initiation of the test. The theoretical derivation of the relationship between these values, and another parameter, the n value, are described by the Poisseulle equation, expressed as,

$$\frac{dv}{dt} = at^{-n} \qquad (1)$$

where, v = water-filled pore volume, mL
t = time, in seconds
a,n = constants

Equation (1) can be used to define the decay in absorption rate with time. The slope of the Log(ISAT) versus Log(time) graph, Figure 6, gives the n value, which can be used with the ISAT-10 (ISAT measurement taken at 10 minutes) to provide a meaningful summary of the complete set of results(14). However, at this early stage of the work only the 10 minute values have been considered.

Table 1 gives examples of the range of ISAT-10 values of grade 35 N/mm^2 concretes made with different combinations of portland cements, PFA and GGBS, cured in various environments. It can be seen from this that a central factor affecting the absorptivity of concrete is curing. Varying curing for the same concrete mixture can produce absorptivity values of ±63% about a mean value, but even for the same curing, material differences can cause variations of up to ±24% of the mean value. Site concrete has several other factors which cause the concrete quality to vary, such as workmanship, control over material quantities, degree of compaction, and temperature.

MEASUREMENT OF DURABILITY

Freezing and Thawing Deterioration

The durability of a number of concrete mixes to alternate freezing and thawing, carbonation, chloride ingress and abrasion were measured and are plotted against ISAT-10 in Figures 7-10. The mixtures, curing regimes and workability reflect the concrete commonly used in construction, and form the basis of a major research programme at Dundee University(11,13,17). Details of the range of variables tested can be obtained from Figures 7-10.

It is not be normal practice to use non-air-entrained concrete for frost resistance, but in order to establish the potential of the ISAT test to measure frost resistance non-air-entrained concrete was used in this study. The total number of freezing and thawing cycles, to ASTM C666 (Part A)(18), to cause failure of non-air-entrained concrete in terms of length change, are plotted against corresponding ISAT-10 in Figure 7. This shows all the OPC concrete results, together with general relationships for PFA and GGBS concrete.

The relationship between absorption and frost resistance for OPC concrete is excellent, and has a coefficient of correlation of 0.95. The magnitude of the internal stresses induced by the expansion of water in concrete is affected by the ease with which these stresses can be relieved by movement of water through the pore system, and on the ultimate tensile strength of the concrete. Air-entrained concrete however, which is specified for frost resistance, has discrete spherical cavities which allow the flow of water away from areas of stress. This suggests that the interconnectivity of a pore system would be the controlling factor of frost resistance. The results obtained here show that for non-air-entrained concrete this is not the case, and that an inverse relationship between ISAT and frost resistance exists (ie. high absorptivity, low frost resistance).

It is shown in Figure 7 that PFA reduces the frost resistance of concrete. It has been reported(19) that air-entraining agents need to be used in higher dosages in PFA concrete to give the same air contents as OPC concrete, but unpublished work(20) has suggested that the structure of non-air-entrained concrete makes it more susceptible to frost attack. However, the absorptivity of PFA concrete(14) is lower than that of OPC concrete, and therefore the decrease in frost resistance of PFA concrete is offset in part by lower ISAT for equal grade concrete.

Carbonation

Atmospheric CO_2 penetrates concrete structures, causing a reduction in pore fluid alkalinity, thereby reducing its protection against corrosion of steel reinforcement.

An accelerated carbonation system(21) was used to produce a depth of carbonation over periods equivalent to up to 30 years. The 20-year equivalent carbonation results are shown plotted against the ISAT-10 in Figure 8. Whilst the coefficient of correlation, r, between the parameters across all OPC mixes tested was 0.86, analysis of the individual series would suggest that better correlation exists for specific concrete types. The process of carbonation is affected by both pore structure of hydrated cement paste and its initial pH. These two parameters are altered by the use of pozzolanic materials, which produce a less permeable matrix, but also consume $Ca(OH)_2$ in the process, which reduces the pH. This accounts for the change in the ISAT-carbonation depth relationship when PFA or GGBS is used. It should be noted, however, that both materials caused a reduction in the absorptivity. This means that for equal strength grade concrete, the carbonation resistance of PFA or GGBS concrete would be closer to that of portland cement concrete than judgement on the basis of equal ISAT-10 would suggest.

Chloride Diffusion

The effects of replacing OPC with PFA at 15 and 30% levels by mass, on an equal 28-day strength basis, were studied. The relationship between ISAT-10 and the coefficient of chloride diffusion (D) is shown plotted in Figure 9 for water-cured concrete. Whilst there is no general relationship between the ISAT-10 and chloride diffusion, unique relationships do exist when different binders are considered individually.

The resistance of concrete to the ingress of chlorides is determined by two parameters. Firstly, there is a physical effect, which is controlled by the number of available paths through the pore system of the cover concrete. Secondly, different binders can react with chloride ions to varying degrees(22), and can fix them chemically, and thus retard further ingress. It has been shown(23) that PFA, irrespective of quality, has a higher chloride binding capacity than OPC, and that this chemical response causes the change in the chloride diffusion/ISAT-10 relationship shown in Figure 9.

Concrete mixtures made with different replacement levels of GGBS (30-70% by mass) have also been tested for ISAT, and show a similar beneficial effect as has been noted with PFA, Figure 9. The general relationship, therefore, shows that chloride resistance is significantly affected by binder type. Thus, further considerations of binder chemistry will be required in addition to the ISAT-10 value, which essentially describes the physical nature of concrete.

Abrasion

Although the abrasion resistance of concrete can be readily measured in the laboratory(24,25) it is difficult to measure in-situ. Thus, a simple method which could routinely be applied non-destructively to assess abrasion resistance is highly attractive.

A good correlation (r = 0.95) was found between ISAT-10 and abrasion depth (25) for the OPC, PFA and GGBS concretes.

It is not surprising that the ISAT, which is sensitive to the degree of hydration and the physical characteristics of the surface layers, would give a good measure of the resistance to mechanical attrition.

PERFORMANCE-BASED CLASSIFICATION FOR DURABILITY

A tentative durability classification, based the ISAT-10, is given in Table 2. It is recognised that over the service life of concrete its absorption properties will be affected to a varying degree by microcracking caused by factors such as cyclic heating and cooling, freezing and thawing, loading and unloading and the differences between the coefficient of thermal expansion and E value of the cement paste and aggregate. However, this classification is intended to show the potential of the ISAT for quality control purposes, usually carried out at no later than 28 days. At this relatively early age, the w/c and cement chemistry are likely to be more important than ongoing environmental factors. Furthermore, since the mixtures tested in this study form only a part of a larger research programme, the values chosen are conservative. As future results become available, it will be possible to be more accurate in the classification.

It should also be noted that material differences will require additional considerations to be taken into account as indicated in Table 2, particularly in environments where there are chemically-dominated durability problems, such as chloride ingress and carbonation.

IN-SITU CONDITIONING

This study has shown that the ISAT is suitable for classifying concrete for durability. This means that, in principle, the test could be used on site for both new construction (potential durability) and for existing structures (residual durability). Although variations can arise locally from climatic and microstructural differences, the major problem with site application is the sensitivity of all permeation properties to the moisture content of concrete(7), which can vary greatly.

Little guidance(16) is available for in-situ testing other than "not within two days of rain". This is clearly inadequate. There are two possible methods to overcome this problem. One approach is to attempt to measure in-situ moisture content(26), then back-calculate the absorptivity at a standard moisture content. A more practical approach would be to standardise the moisture content of the test region prior to test.

A vacuum drying system has been developed at Dundee University(27). The system operates by removing moisture by the use of hard vacuum from the surface of the concrete and defines the standard moisture condition for testing by the use of a humidity indicator salt. This has advantages in that it can be used either in the laboratory or in-situ, and initial results are encouraging. This suggests that the proposed classification for durability can indeed be developed for in-situ applications.

CONCLUSIONS

1. The Initial Surface Absorption Test can be used as a performance-based classification for specifying concrete durability. Close relationships exist between the ISAT-10 results and different aspects of durability for a selection of concrete mixes, with varying grade, cement type, maximum aggregate size and curing environment.

2. Excellent correlation with durability aspects was found where the physical nature of the concrete was the dominating factor for resisting deterioration, such as with freeze/thaw and abrasion resistance. Where chemical processes have an effect on durability, such as is the case carbonation and chloride diffusion, the correlation between absorption and durability is less strong, but unique relationships do exist for individual binder types.

3. A tentative durability classification for concrete, based on the ISAT-10, has been proposed. Although much work remains to be done in this area, such a classification has the potential to overcome many of the present limitations of conventional specifications. This could be further developed to allow active design for durability, with a measurable quality-control parameter which could be checked against a performance-based specification.

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TABLE 1 — EFFECT OF CURING AND MATERIAL VARIATION ON THE ISAT OF GRADE 35 N/mm^2 CONCRETE

CURING	**28 DAY ISAT-10 $ml/m^2/sec\ x10^{-2}$**		**VARIATION ARISING WITH DIFFERENT MATERIALS**
	Range	**Mean**	
Air	155 - 255	205	±24%
3 days water	83 - 105	94	±12%
7 days water	70 - 84	77	±10%
28 days water	58 - 70	64	±9%
Median	157		
Overall Range	58 -255		
% Variation with curing	±63%		

TABLE 2 — TENTATIVE CLASSIFICATION FOR CONCRETE DURABILITY BASED ON THE ISAT

DURABILITY CLASSIFICATION RANKING	**ISAT-10, $ml/m^2/sec \times 10^{-2}$**	**ADDITIONAL CONSIDERATIONS**
1	<50	**Chloride Diffusion** With PFA or GGBS, increase ranking by 2 divisions **Carbonation** With PFA or GGBS, decrease ranking by 1 division **Frost Resistance** With PFA, decrease ranking by 1 division
2	51-70	
3	71-90	
4	91-110	
5	>110	

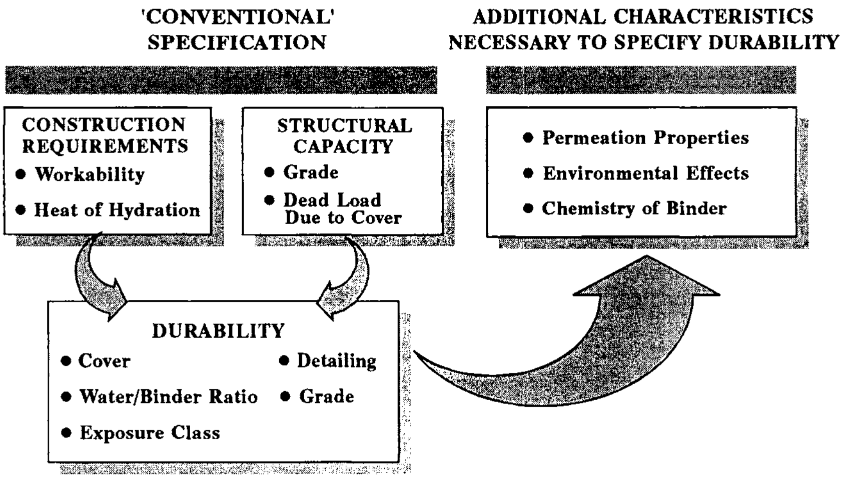

Fig. 1—Specification requirements for durable concrete

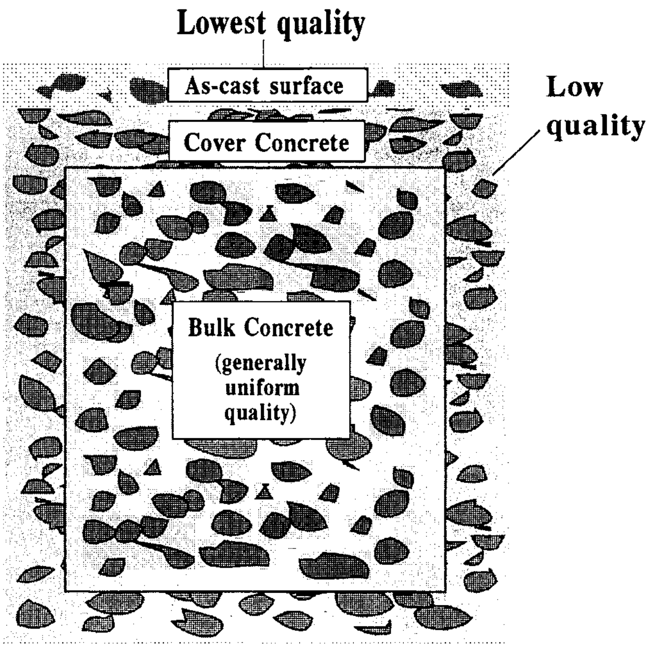

Fig. 2—Variations of concrete quality across a section (from Ref. 12)

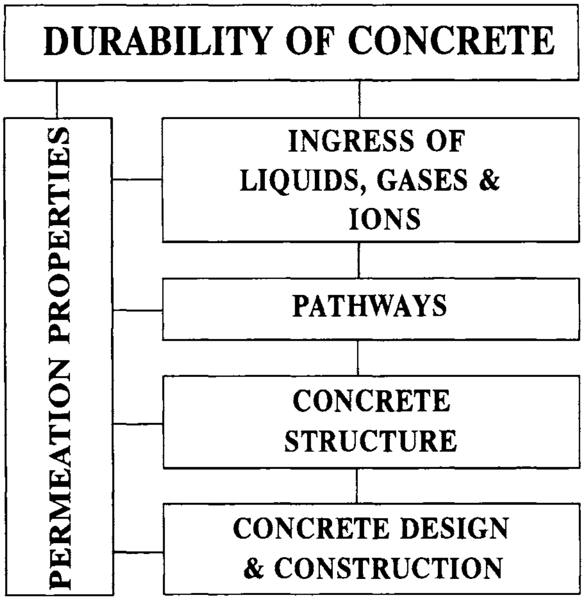

Fig. 3—Relationship between permeation properties, concrete structure, and durability

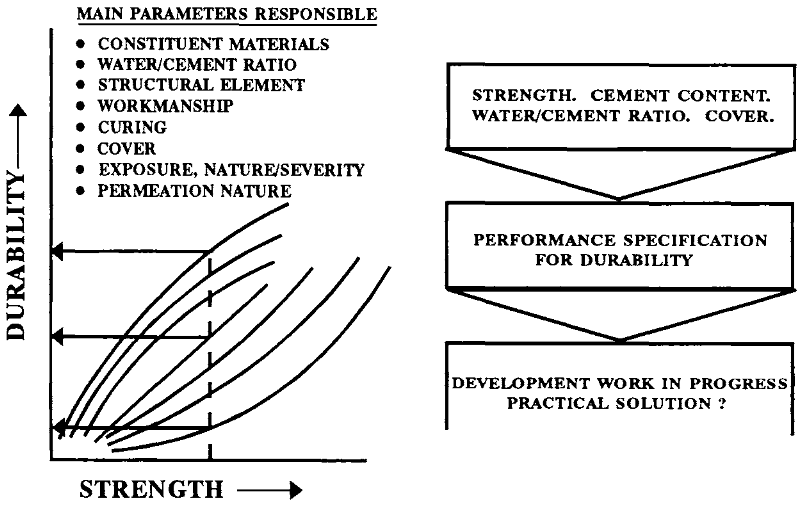

Fig. 4—A critique of the approach to achieving concrete durability

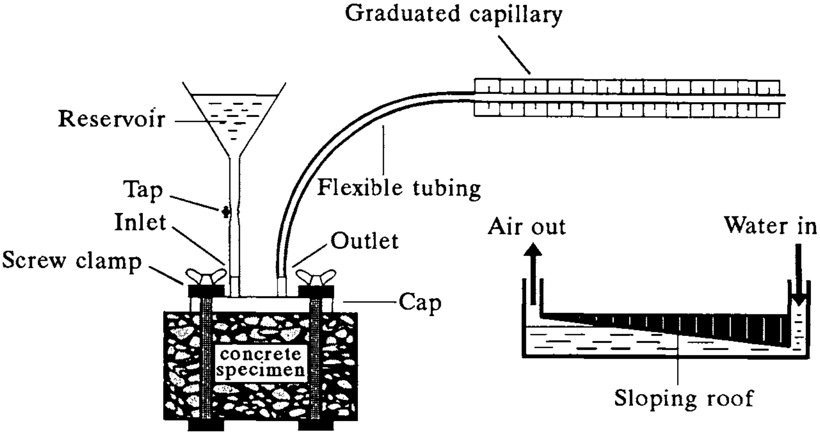

Fig. 5—General layout of the ISAT equipment and detail of the sloping-roof cap

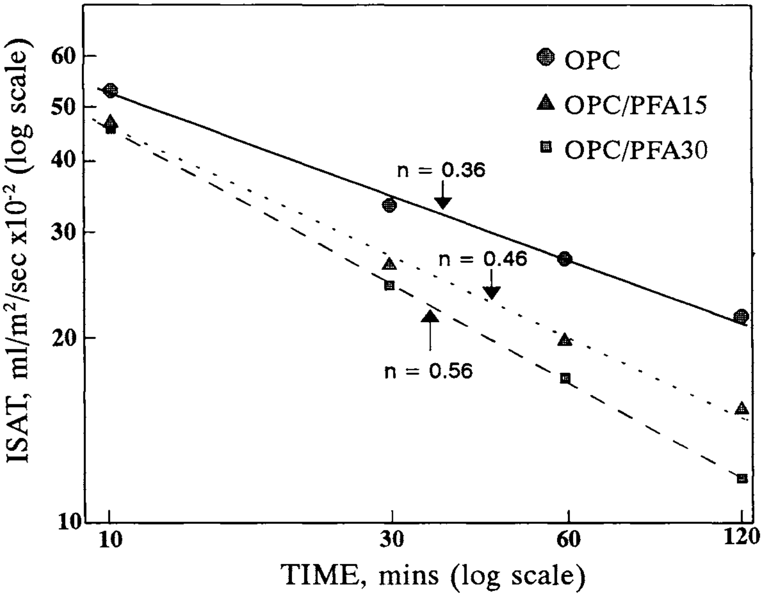

Fig. 6—Derivation of n values from ISAT measurements

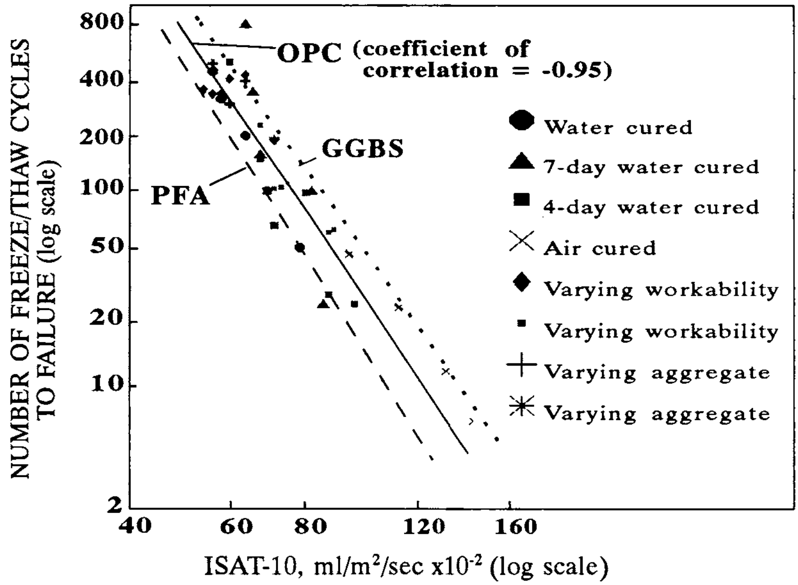

Fig. 7—Relationship between number of freeze-thaw cycles to failure and ISAT-10

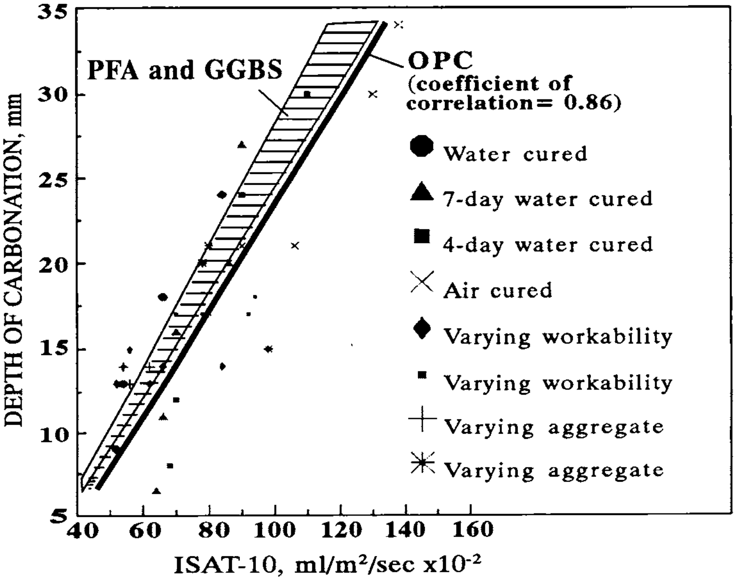

Fig. 8—Relationship between carbonation depth and ISAT-10

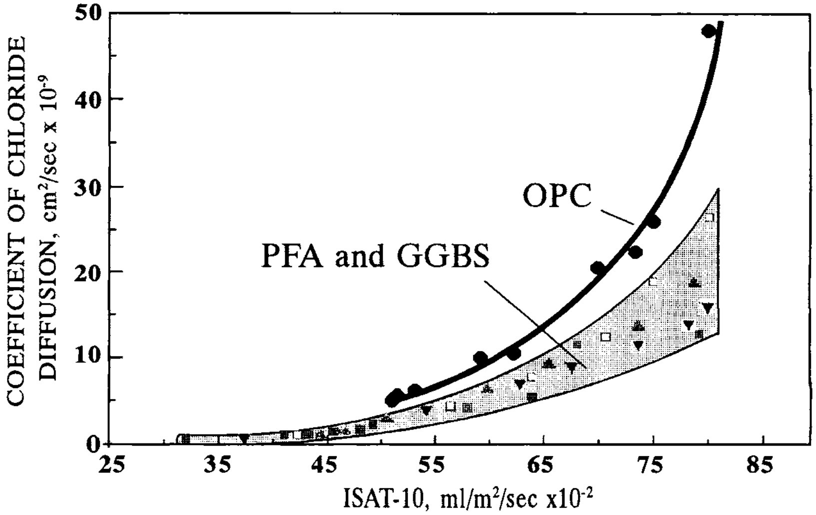

Fig. 9—Effect of PFA and GGBS on the ISAT-10 versus chloride diffusion coefficient relationship

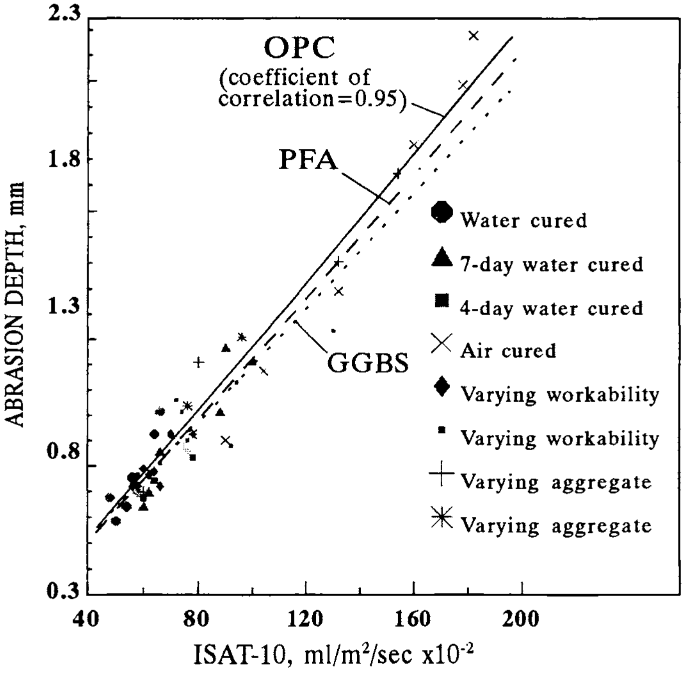

Fig. 10—Relationship between depth of abrasion and the ISAT-10