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ISAT PREDICTION OF CONCRETE DURABILITY

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ABSTRACT

This paper deals with the assessment of durability potential of concrete by measurement of it's absorption properties. The durability aspects covered were freeze-thaw, carbonation, chloride diffusion and abrasion. The test method for determining the absorptivity was the Initial Surface Absorption Test (ISAT), used essentially as defined in BS1881, but with several modifications to enhance it's application as a laboratory test.

The results from accelerated carbonation, freeze-thaw attack, abrasion and chloride diffusion tests are plotted against those of the ISAT, and basic statistical analyses performed to ascertain the certainty with which these aspects of durability may be predicted from the absorption. The results obtained from different concrete types, including varying grade, workability and maximum aggregate sizes and the effect of curing are considered. In addition, the effect of PFA on co-efficient of chloride diffusion rate is discussed.

INTRODUCTION

Unacceptably high repair and maintenance costs are incurred in the lifespan of many concrete structures. This is the case even when increasingly stringent durability provisions are recommended in the various national and international Codes of Practice for the design and construction of concrete structures, for example BS8110(1) in the United Kingdom. Clearly, there is room for improvement in the way we specify both the concrete materials and the construction methods.

One possible way forward could be to specify concrete by parameters that would reflect its durability more realistically, taking on board the influence of the nature of the constituent materials and their proportions, the workmanship and curing afforded during and after construction and the severity of the exposure conditions. These combined effects can be very complex and therefore the chosen durability parameter should be sufficiently sensitive to respond to changes in the internal structure of concrete. Then there is also the question of the ease with which such durability specifications can be adopted in practice.

CURRENT SPECIFICATIONS FOR DURABILITY

Current British Standards(1,2) take the view that concrete can be protected against deterioration using specifications that are indirectly related to durability, such as maximum water/cement ratio, minimum cement content, strength and cover to reinforcing steel. Notwithstanding the obvious merits of this approach, such as the relative simplicity of the mix design procedures and compliance testing for strength, there are several problems with the philosophy. It has been shown (Figure 1) that, as well as general bulk parameters, an accurate specification for durability requires to have a performance-based element to take into account the variation arising from factors not controlled by current standards, and which can cause the potential for durability of concrete to differ widely.

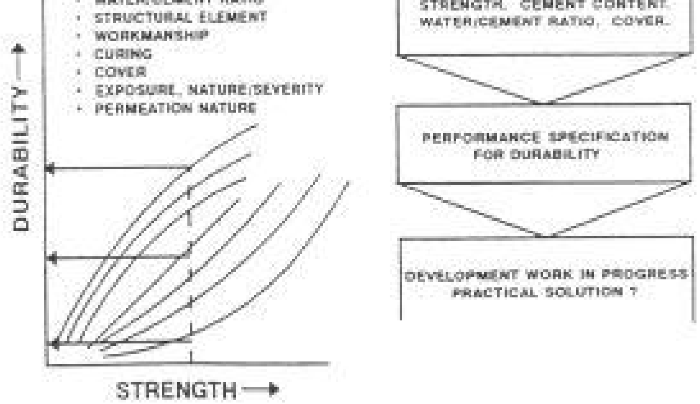

Figure 1. A critique of the current specification for durability

For instance, the chemical and physical properties of cements can vary. In particular, the use of pozzolanic cement replacement materials is growing, as indicated by their increasing acceptance by the British Standards(2). These materials significantly affect the pore structure of concrete(3) and therefore it's ability to resist the ingress of aggressive environmental fluids and ions. The use of pulverized-fuel ash to replace cement on an equal strength or water/cement ratio basis, is known to significantly reduce the rate of chloride ingress into concrete(4).

The quality of site concrete is also likely to vary considerably with depth due to moisture loss by evaporation from the surface layers, which protect the steel reinforcement(5).

PERFORMANCE-BASED SPECIFICATION FOR DURABILITY

It is possible to measure the performance of concrete by means of accelerated durability tests in the laboratory. Even so, such tests tend to be time consuming and costly. For example, to simulate 30 years exposure to carbonation still takes upwards of 6 months(6) and determination of the coefficient of chloride diffusion can take up to 18 months(7).

The movement of fluids and ions through concrete is controlled by the size, number, interconnectivity and tortuosity of the pore system. For a given quantity of cement and water in a mix, the pore size distribution and interconnectivity can be affected by the type of cement used. For example, PFA is known to cause pore blockages, which reduce the ease with which fluid movement can occur, although the overall porosity may not be significantly affected(8). Therefore, if the performance of concrete could be quantified in different exposure environments by means of parameters reflecting the active pore system, a more realistic appraisal of durability could be obtained, either for new or existing structures.

PERMEATION FINGERPRINTING OF CONCRETE

The permeation properties of concrete measure the rate at which fluids or ions pass through concrete under their respective mechanisms (absorptivity, permeability and diffusivity). These properties are sensitive to changes in the pore system caused by cement content and type and degree of curing, and can be assessed by simple laboratory indicator tests. Such measures therefore, can provide a 'fingerprinting' of the active pore system, which can be used to make the necessary links between concrete microstructure and durability, Figure 2.

This study has taken the approach that the quality of the surface layers of concrete, which form the first line of defence against environmental aggressors, is important to the ultimate durability of concrete, and can therefore be used as a predictive measure. The study was carried out with the Initial Surface Absorption Test (ISAT) which is an economical and convenient method for

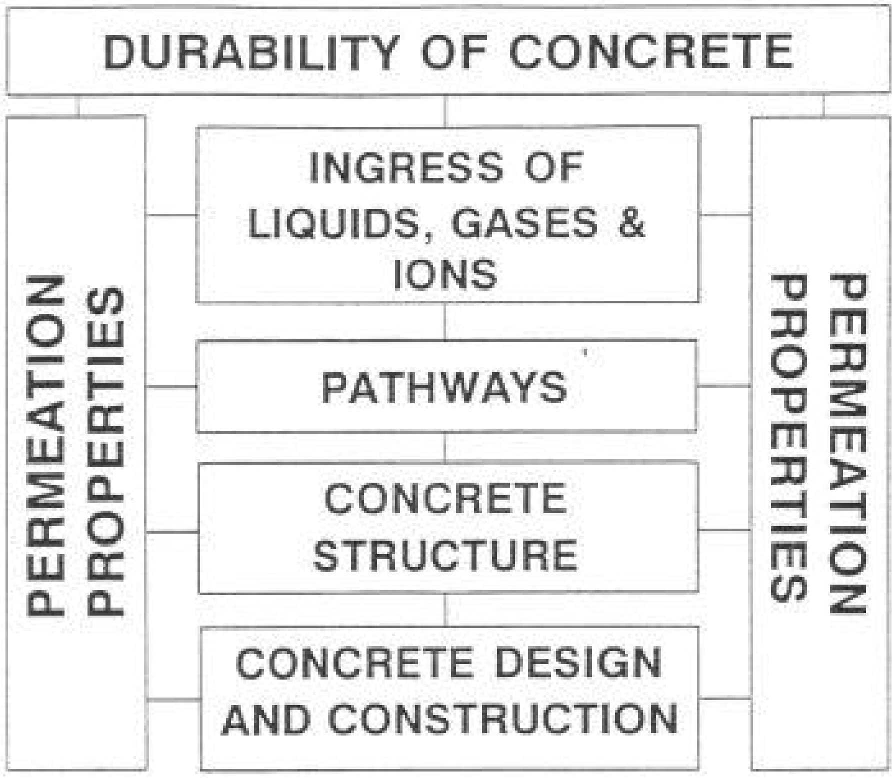

Figure 2. Relationship between permeation properties, concrete structure and durability

INITIAL SURFACE ABSORPTION TEST (ISAT)

The Initial Surface Absorption Test apparatus used in this study is shown in Figure 3. Although the layout embraces the general principles of the Standard method(9), significant modifications and improvements have been made(10) to both the apparatus and test methodology . The test is basically of the form of a flexible U-tube, with a cap of known area clamped to the test surface. One vertical branch acts as a reservoir, which can be isolated by a tap, and the other

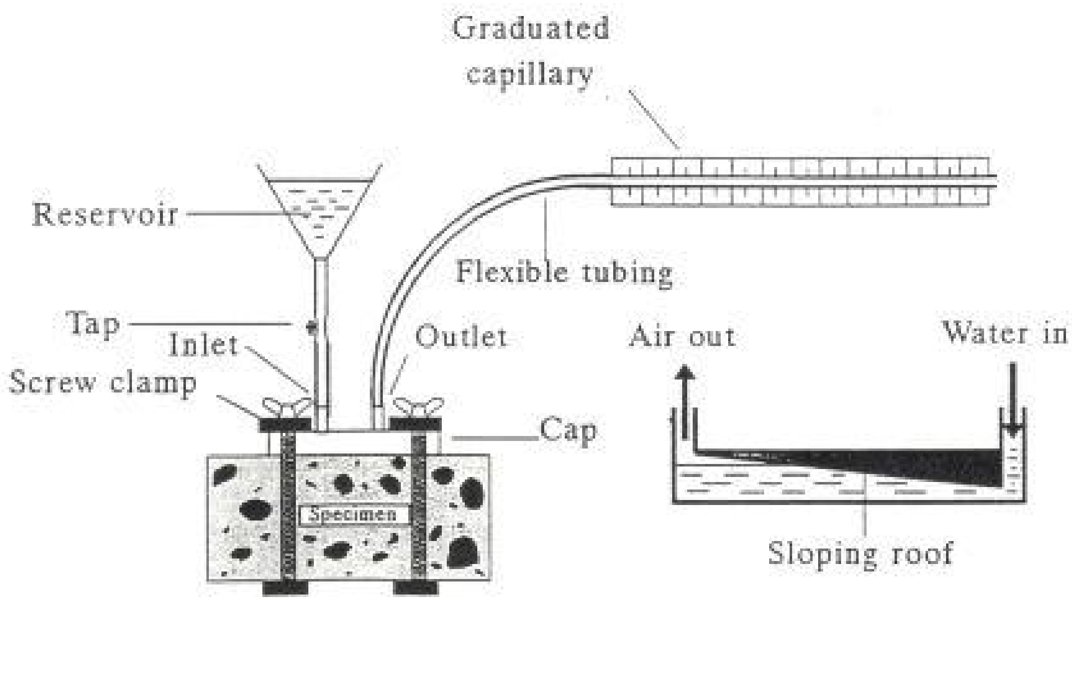

Figure 3. Schematic ISAT apparatus

is connected to a calibrated capillary tube and the latter is used to measure the rate of absorption of water into the concrete below the cap on closure of the tap.

The Standard recommends that ISAT measurements should be taken at 10, 30, 60 and 120 minutes after the initiation of the test. Using this method, the slope of the Log(ISAT) versus Log(time) graph (the n value), as indicated for different 50N/mm^2 concretes in Figure 4, can be used in conjunction with the ISAT-10 (ISAT measurement taken at 10 minutes) to provide a more meaningful summary of the complete set of results(11), although for simplicity, only the 10 minute values (ISAT-10) are used in this study.

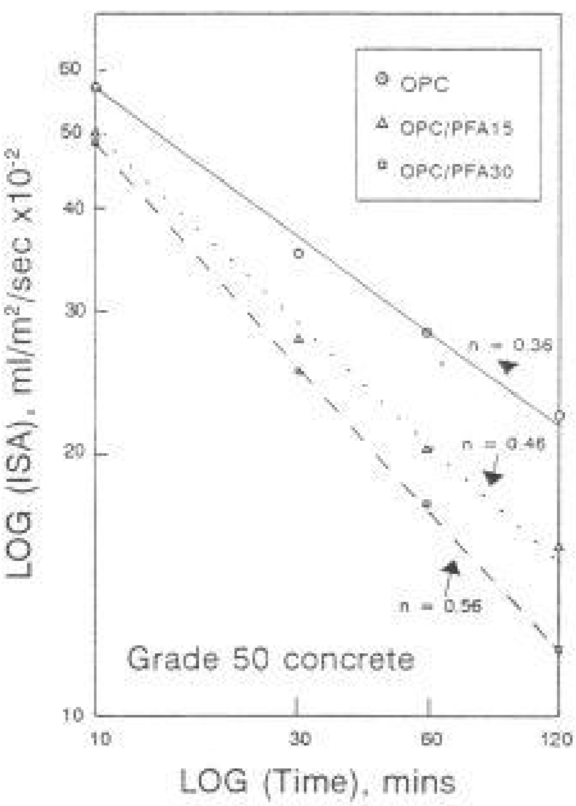

Figure 4. Log(ISA) versus log(time) relationships

Table 1. Effect of cement type on ISAT of water-cured concrete

CONCRETE TYPE (Strength = $50N/mm^2$	ISAT-10, $ml/m^2/sec$ x10-2
Normalweight 20mm aggregates	
OPC	67
OPC/PFA15	60
OPC/PFA30	58
RHPC	74
RHPC/PFA15	64
RHPC/PFA25	60
OPC/GGBS30	52
OPC/GGBS45	50
OPC/GGBS60	48
OPC/GGBS70	47
OPC/MS10	37
Normalweight 10mm aggregates	
OPC	58
Lightweight Aggregate	
12mm	140
6mm	80
Lightweight fines	67

Table 1 gives examples of the range of ISAT values for water-cured, equal 28-day $35N/mm^2$ strength concretes tested at Dundee University using different pozzolanic materials and aggregates. These have a mean of 64 $ml/m^2/sec$ $x10^{-2}$ with a standard deviation of around 23 (some 40% of the mean value). It should be noted that this variability represents the minimum possible, since the concretes tested were cast, water-cured at a constant temperature and tested under strict laboratory conditions, with only the choice of constituent materials varying.

Site concrete has several other factors which cause the concrete quality to vary. The workmanship, degree of compaction, moisture availability and ambient temperature can all affect the quality of the concrete in structures. These factors, which are more or less uncontrolled by the present Standards, in combination with the variation arising from materials (Table 1), suggest that parameters such as concrete grade or material quantities are not sensitive enough to specify durability accurately, and that a performance-based specification approach is required.

PREDICTION OF DURABILITY WITH THE ISAT

To estimate the potential durability of concrete mixes to various environmental effects, the rate of freeze/thaw attack, carbonation, chloride ingress and abrasion were measured directly on the same concrete mixes as were used for ISAT testing. The test methods used may be obtained from the literature(12,6,7,13). These results were then used to construct scatter plots of ISAT-10 vs durability parameters, which are discussed hereafter.

A number of different concrete mixes have been tested for both ISAT and durability so far in the current research programme, as shown in Table 2. The pozzolanic cement replacement mixes listed in Table 1 are also part of the programme, but the durability testing of some of these is still in progress. Whilst the full set of results is not available as yet, the suggestion at this preliminary stage is that the absorptivity of the mixes in Table 1 relates well with the durability. For example, the lowest coefficients of chloride diffusion and absorption seem to be found with GGBS concrete.

Table 2. Concrete mixes tested

CONCRETE MIX	MIXES TESTED			
	FREEZE/ THAW	CARBONATION	CHLORIDE DIFFUSION	ABRASION
Normal concrete, water cured	■	■	■	■
Normal concrete, cured in water for 7 days	■	■	-	■
Normal concrete, cured in water for 3 days	■	■	-	■
Normal concrete, air-cured	■	■	■	■
Variable workability concrete, 25mm-collapse slump, water cured	■	■	-	■
Variable workability concrete, 25mm-collapse slump, air-cured	■	■	-	■
Variable maximum aggregate size, 10-40mm, water-cured	■	■	-	■
Variable maximum aggregate size, 10-40mm, air-cured	■	■	-	■
15% PFA concrete, water-cured	-	-	■	-
15% PFA concrete, air cured	-	-	■	-
30% PFA concrete, water-cured	-	-	■	-
30% PFA concrete, air-cured	-	-	■	-

- not tested

Freeze/thaw attack

Cyclical freezing and thawing of concrete causes degradation as a result of the expansion of water within the pore system on freezing. This induces internal stresses, which causes cracking if the concrete cannot either withstand the stress, or accommodate the expansion (as in the case of air entrained concrete).

The number of cycles to failure for mixes tested for freeze/thaw resistance (Table 2), are shown plotted, against corresponding ISAT-10 in Figure 5. The coefficient of correlation, r, in this case, is 0.95.

This is a relatively close relationship, and was not expected at the outset of the work. The internal stresses set up by the expansion of water in concrete are dependant upon the ease with which these stresses can be relieved by water movement, and on the ultimate tensile strength of the concrete. Air-entrained concrete, which is specified for freeze/thaw resistance, has discrete spherical cavities which allow the flow of water away from areas of stress. This suggests that interconnectivity of a pore system would increase freeze/thaw resistance. This would not appear to be the case, however, as Figure 5 shows an inverse relationship between ISAT and freeze/thaw resistance (ie high absorptivity, low freeze/thaw resistance). The ISAT test does, however, correlate very well with strength(10) for a particular type of cement, and therefore it would seem that concrete grade is of greatest influence for non-air-entrained concrete mixes.

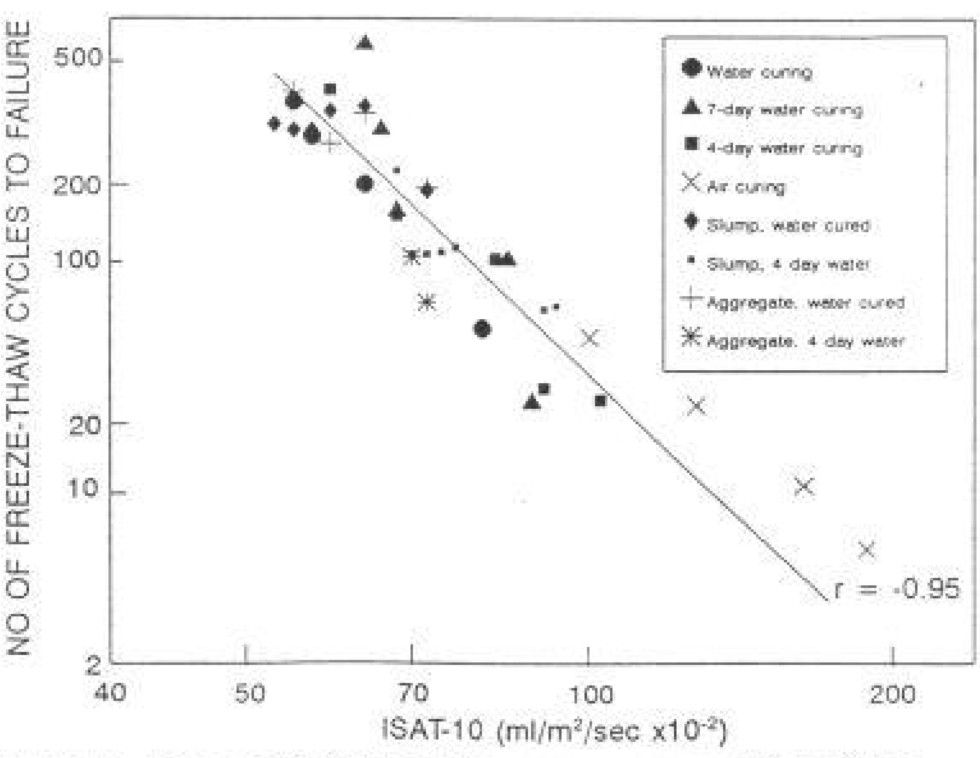

Figure 5. Freeze/thaw results vs corresponding ISAT results

Initial freeze/thaw and ISAT results from non air-entrained GGBS concrete suggest that the use of GGBS as partial replacement of OPC increases freeze/thaw resistance and reduces the ISAT. This is in line with the relationship shown in Figure 5, and means that the relationships presently being found in this study are likely to extend further to include other concretes made with other binder types.

Carbonation

Carbon-dioxide from the environment penetrates into concrete structures, and causes a reduction in the alkalinity of the pore fluid, thereby reducing the passivating effect on steel reinforcement. This promotes a breakdown of the protective steel oxide layer, and can result in steel corrosion, with its associated problems for structures. The process of carbonation is much slower than that of contamination by chlorides, and is not likely to become a serious concern for structures in the first half of their design life.

The 20 year equivalent results obtained from the accelerated carbonation tests (Table 2) are shown plotted in Figure 6, against corresponding ISAT values. The coefficient of correlation between the parameters, r, considering all the different mixes tested, was 0.86. A close visual examination of the data shows, however, that for individual series of concrete mixes, closer correlation may be found. The concretes tested for carbonation depth were all OPC concrete mixes, and therefore whilst the process of carbonation is affected by both the pore structure of the hydrated cement paste and its pH, (the detrimental aspect of carbonation is mainly related to pH reduction) it is unlikely that the latter of these would be significantly different in any of the mixes tested. Assuming no chemical effects, this means that the spread shown around a straight-line relationship is due to the effects of curing, water content and aggregate/matrix interstitial zone effects.

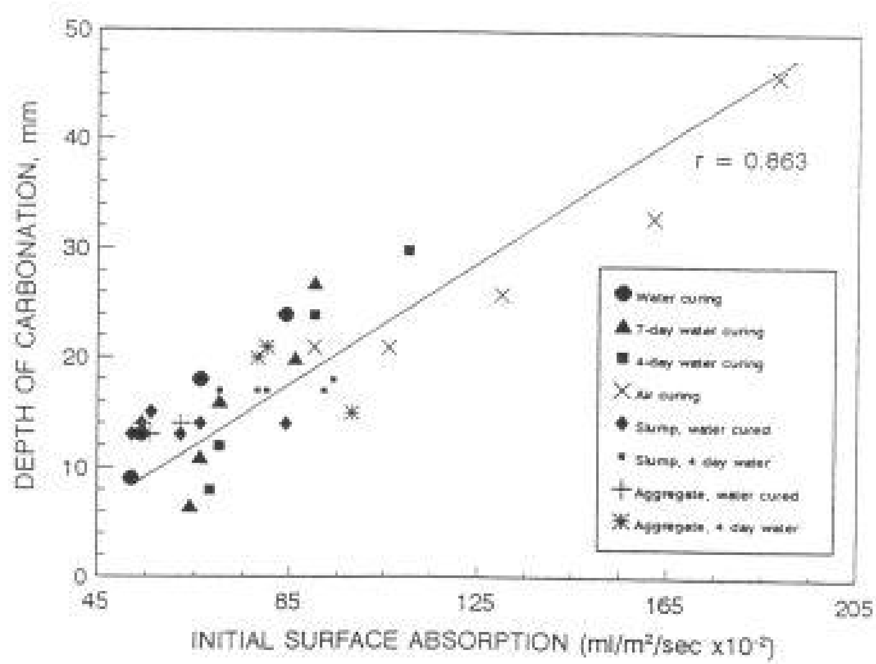

Figure 6. Carbonation depth after 20 weeks accelerated

Chloride Diffusion

This section of the study investigated the effects of replacing OPC with PFA at 15 and 30% levels, Table 2. The ISAT-10 vs chloride diffusion coefficient results are shown plotted in Figure 7 for water and air-curing. These show that there is no general relationship between the surface absorption and chloride diffusion rate of concrete, but that unique relationships do exist when single binders are considered individually. The reasons for this are discussed below.

The resistance of a cement to the ingress of chlorides is determined by two parameters. Firstly, there is a physical effect, controlled by the number of active paths through which the chlorides move. Secondly, cements react with chloride ions to differing degrees(15), and bind them chemically thus preventing further ingress. It has been shown(4) that PFA has a higher chloride binding capacity than OPC, and this difference in chemical response causes the downwards shift in the chloride diffusion versus ISAT-10 curves with increasing PFA content (Figure 7).

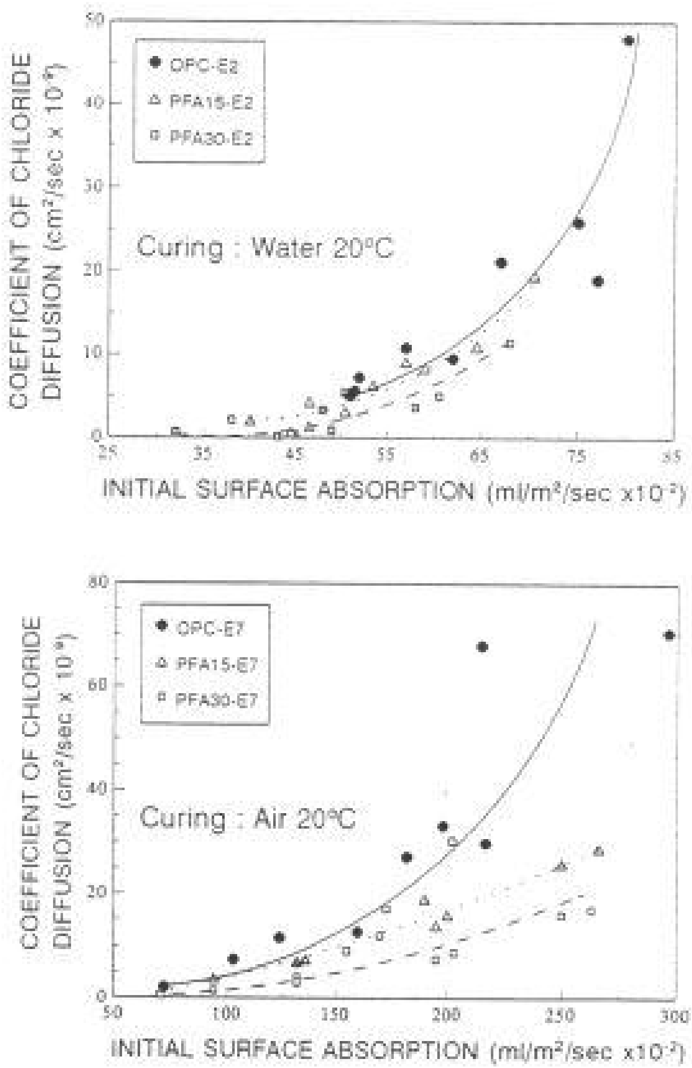

Figure 7. Chloride diffusion rates versus corresponding ISAT results for OPC and OPC/PFA concrete.

In the wider study, concrete mixes made with different replacement levels of GGBS have also been tested for ISAT (Table 1). Preliminary chloride diffusion results for these mixes are suggesting that the reduction in absorptivity shown in Table 1 is matched by a corresponding decrease in coefficient of chloride diffusion, although, as with PFA concrete, relationships between the variables only exist for individual GGBS contents.

Abrasion

The abrasion tests were carried out in accordance with ASTM C-799(13) as modified by Dhir et al(14). The abrasion depth test results obtained are shown in Figure 8, plotted against the corresponding ISAT-10 results. As with the freeze/thaw results, these show good correlation (r = 0.95). Abrasion is a purely physical effect, and it was expected that a test which measured the absorptivity of the surface layers of concrete, and therefore was sensitive to the degree of hydration and strength level would be in proportional relation to physical attrition.

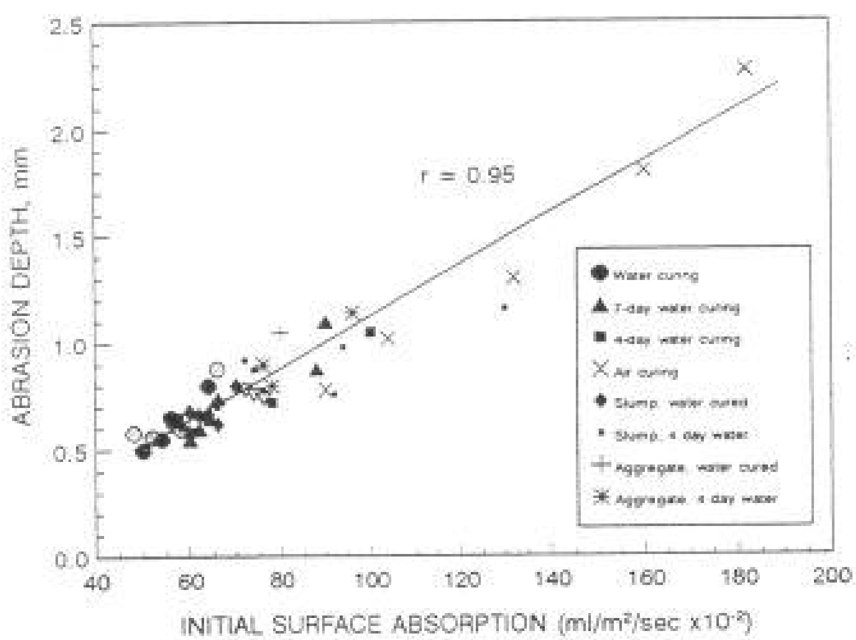

Figure 8. Abrasion results vs corresponding ISAT results

IN-SITU CONDITIONING

This study has shown that the ISAT can be used as a tool for more accurate prediction of durability than by the use of mix proportions and grade. This means that the test has the potential to be exploited in-situ for both new construction (potential durability) and for existing structures (residual durability). However, the absorption and other permeation measurements (permeability and diffusivity) of concrete are initially sensitive to its moisture state. To produce meaningful results, standardisation of the moisture content under site conditions is clearly an essential requirement before such measurements can be applied as a means of specifying for durability.

The British Standards offer little advice for in-situ absorption testing other than "not within two days of rain". Obviously, this is insufficient to cover all situations to be met on site with variations arising from sheltered or exposed sections. A preconditioning method to allow for both site and laboratory data to be compared is required to maximise the benefits to be gained from measurement of permeation properties.

Work is underway at Dundee University on the development of a vacuum drying system for preconditioning concrete prior to test(16). The test operates by removing moisture under vacuum from the surface of the concrete, with equilibrium being defined by an humidity indicator salt. This has the advantage of suitability for either laboratory or in-situ use. Initial results are extremely encouraging, and are being published in the Magazine of Concrete Research. The method is now fully operational, and is being developed further for site use.

CONCLUDING REMARKS

The ISAT has potential for performance-based specification of concrete mixes, for use in-situ or in the laboratory. Close relationships have been found to exist between ISAT results and various aspects of durability for a selection of concrete grades, types and curing environments.

Closest correlation between ISAT and durability was found with durability aspects concerned solely with the physical nature of the concrete, such as freeze/thaw attack and abrasion. Where secondary chemical effects are present, such as with carbonation or, more particularly, chloride diffusion, the relationship with absorption is less strong, although unique relationships do exist if only one cement type is considered.

The work at Dundee University in this area is continuing, with many more concrete types, particularly those containing pozzolanic materials, being tested for durability and permeation properties. The new results which are emerging strengthen the belief that durability specification can be improved by using permeation properties. As we move into the European scene over the next few years, we will encounter far greater variation in our materials as cement imports from other countries increase. This further emphasises the need for performance-based durability criteria in the Standards.

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