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Near-surface characteristics of concrete: assessment and development of in situ test methods*

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Contribution by F. D. Lydon and M. Al. Odaallah

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The authors have provided a considerable amount of test data, carefully and methodically obtained, which should certainly have a major impact on studies in this area of concrete technology. Their work, as reported, gives rise to a number of questions some of which are caused by the need for brevity in the paper and others which are prompted by attitudes or conclusions which may not be supported by the data.

It would be helpful to know to which curing environment in Table 2 the data in Figures 2, 3 and 5 apply. Why was the 10 min ISA value chosen? (It is appreciated that early work on water absorption and freeze/thaw resistance of laboratory specimens showed better correlation with 10 min values of the former than with 24 h ones; it would be interesting to know why, say, the 30 min or 1 h values of ISA were not chosen, in the present work, and whether they indicated any improvement, or otherwise, in correlations.)

It is always difficult to arrive at a consensus about relative humidity for test purposes and there is probably seldom a 'correct' value. But is not the 55% RH rather low? The advantage of increased drying rate may be outweighed by the disadvantage of greater irreversible microstructural changes—or it may not. Have the authors any thoughts on that?

A rather fundamental aspect of all properties associated with permeability testing is the assumption that the property measured is closely related to the accessible pore structure which, in turn, is closely related to composition and curing history; thus a change in the observed measurement implies a change in composition and/or curing. The concrete is assumed to have a particular structure which, in effect, defines its 'quality'. Because accessibility to the permeating fluid is affected by the moisture content it is evident that two 'identical' concretes, of identical 'quality', will exhibit different measurements of the property if they contain different proportions of moisture. However, if they have identical proportions of moisture then the observed measurements will be identical. Hence the need for conditioning. But it is extremely important that the conditioning does not alter the 'quality'—the pore structure—in a way that significantly alters the observed measurement. It is to be expected that a definite correlation will be seen between ISA values and moisture content (or weight loss on drying) and if there is little change in accessible porosity then only the moisture content, but not the drying history, will affect the observed ISA.

Data from Figures 2 and 3 can be used to check this.

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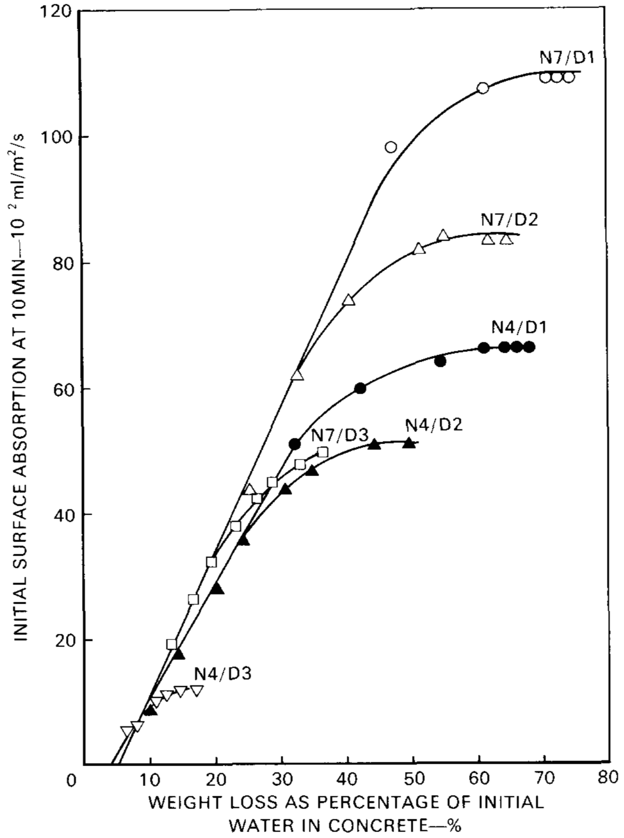
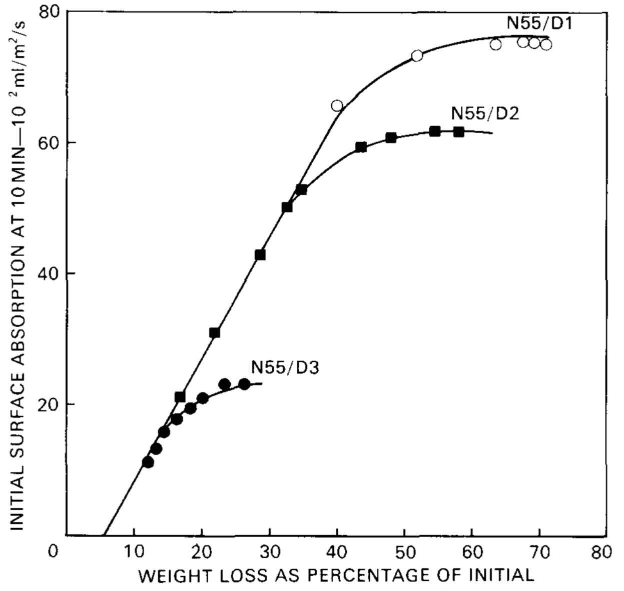
*Pages 183 to 195 of MCR141.



(a) Mixes N4 and N7



(b) Mix N55

Figure I: Relationship between initial surface absorption and weight loss (from Figures 2 and 3 of original paper).

Figure I shows the plots of ISA against weight loss for the different concretes and drying histories. It is seen that for a given weight loss the ISA increases markedly with temperature; therefore the water-accessible porosity increases with temperature and so heating the specimens from 20°C to 50°C and 105°C causes a deterioration in the 'quality' of the concrete.

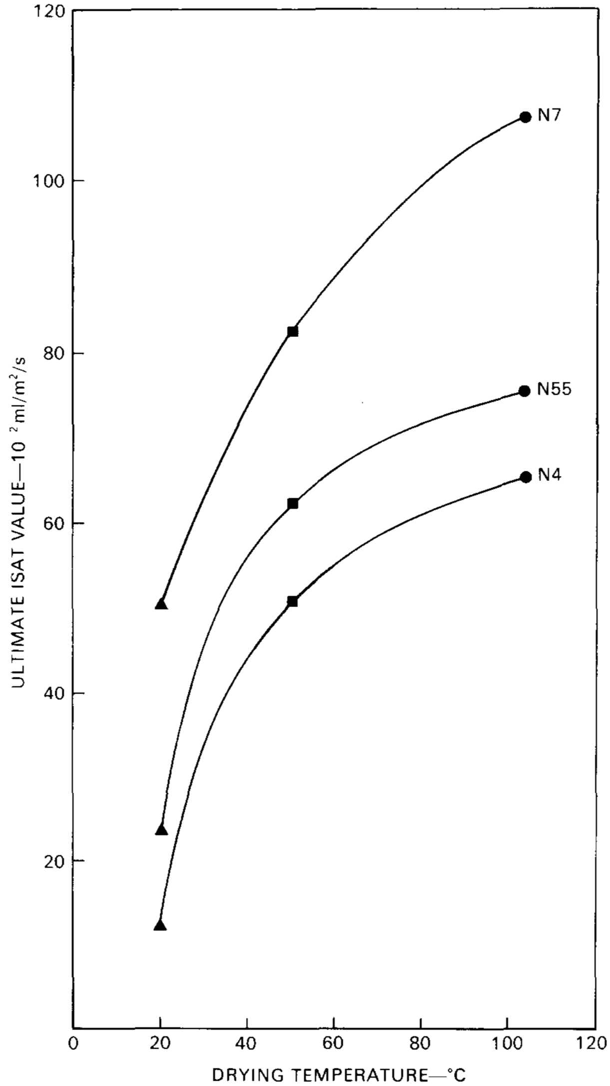


Figure II: Relationship between ultimate surface absorption and drying temperature (from Figures 2 and 3 of original paper).

It is also possible to see the effects on the approximate ultimate ISA values, as shown in Figure II. The effects of the drying are not consistent between the different mixes and so cannot properly be standardized as a component of the testing error. (Incidentally it appears that for the three concretes the ISA begins to be measurable after a loss of about 5% of the initial water content, which is much sooner than the loss after which drying shrinkage is evident in small laboratory specimens. This confirms that water-accessible space is available long before pores, or capillaries, have emptied sufficiently to mobilize the compression responsible for volume reduction.)

The fact noted towards the bottom of page 184 that there is a much bigger change in cube strength, from 30 to 65 N/mm^2 (an increase of 217%), than the corresponding change in ISA values where, for 105°C drying, n varies from 0·30 to 0·40 (an increase of 126 to 161%) is a measure of the decreased sensitivity of

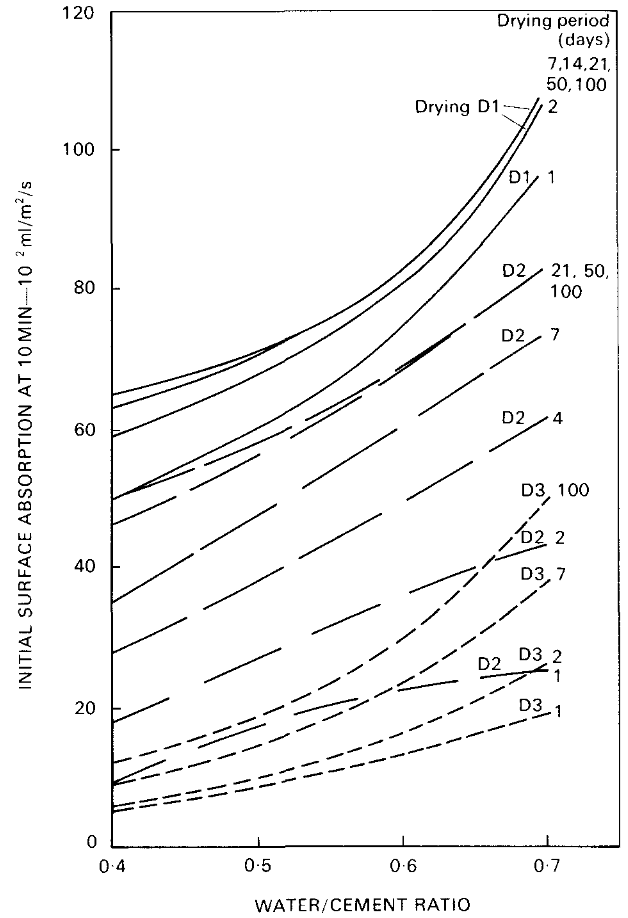


Figure III: Relationship between initial surface absorption and water/cement ratio (from Figures 2 and 3 of original paper).

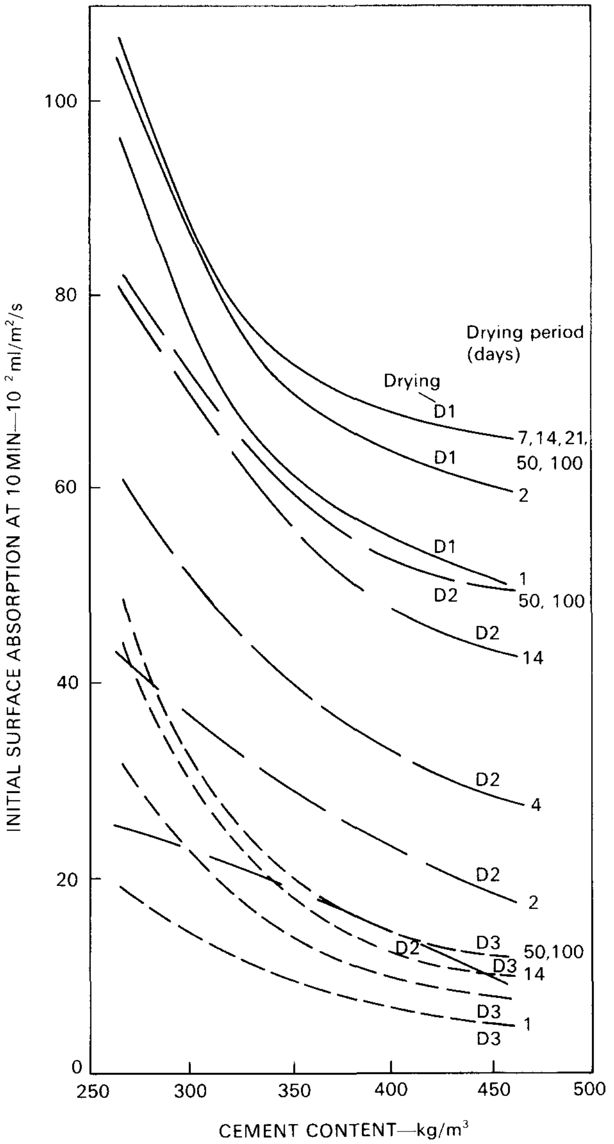


Figure IV: Relationship between initial surface absorption and estimated cement content (from Figures 2 and 3 of original paper).

the ISAT, because of the increased porosity of the concrete.

Figures III and IV show derived plots of ISA against water/cement ratio and cement content, respectively, for the three drying temperatures. The forms of the relationships are interesting, with drying at 50°C showing a much wider range of ISA values than drying at 20°C or 105°C. One of the difficulties of drying at such a temperature is the effect it has on the degree of hydration during drying. Byfors(21) shows an increase of 100%, at 16 h, due to heating at 38°C instead of 20°C. Presumably the precise effect is dependent on the rate of evaporation relative to the rate of hydration, which may vary with initial water/cement ratio and with drying time. Several years ago(22) an arbitrary 52°C for 19 h followed by air drying to constant weight was tried, and subsequently(23) other regimes were used: (1) sealing for 27 days after demoulding followed by drying at 40°C; and (2) water curing at 20°C for 2 days, air drying at 68% RH for 5 days followed by drying over silica gel to constant weight. But observed behaviour can be complicated and difficult to interpret. Perhaps, eventually, a method along the principle discussed by Parrott(24) might become practicable, using counter-diffusion to displace pore fluid by another, low surface-tension, fluid. In the meantime, drying at 105°C for a few days or at 50°C for longer does not seem to be very suitable.

Understandably, in such an extensive investigation, results have been reported for one type of aggregate only; do the authors anticipate significant effects where different aggregates are used?

A direct connection is made, on page 185, between Figure 2 and air drying on site; how is such a connection justified? As the authors commendably point out, the engineer should recognize the factors that will affect the moisture condition of the in situ structure when analysing data obtained. They presumably recognize these themselves; is it not therefore misleading to use air drying of cubes at 20°C and 55% RH to indicate the minimum air-drying period of 7 days (or 14 days) for site testing? Likewise what justification is there for extrapolating from Figure 5 to Table 4 and for the concomitant conclusion? (page 186). Clearly a rigorous study of the effects of changes in controlled

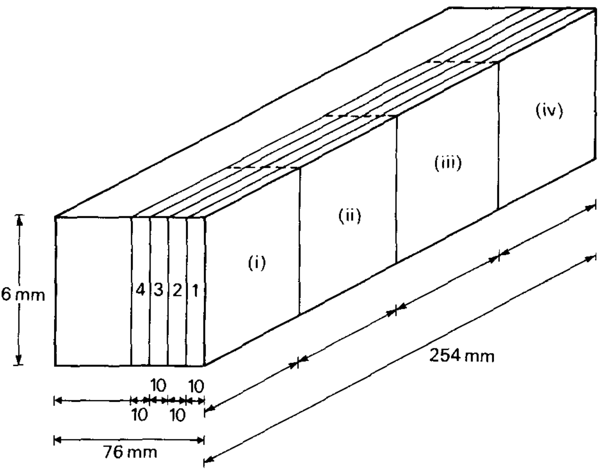


Figure V: Positions and directions of layers sawn from test prism for porosity check.

variables in the laboratory on various properties of concrete and attempts to understand test systems properly (which produce answers that tend to be highly specific) are essential. To presume properties for site concrete is not yet realistic.

The effects of specimen size on mean ISA values and on variability are interesting. The standard deviations are 5·1, 4·2 and 3·9 × 10^{-2} ml/m^2 s; is there a significant difference between these? If there is this means that the number of 100 mm cubes should be correspondingly increased to give the same reliability to the mean values as for the 150 mm ones; if there is not then the same number suffices. In view of the object and nature of the ISAT is it not more convenient to use the smaller size, rather as is done for cube strength? The fact of the different mean ISA values is probably not relevant.

The comment that the surface absorption of the OPC and pfa mixes is similar and that pfa can effectively replace part of the cement without adversely affecting absorption properties (page 187) perhaps needs modification in different circumstances. Table I shows some data[25]. The ISA values are all low but the general trend indicates the well established benefit of some water curing; the presence of pfa, as filler, does not seem to help much.

The alleged limitation of the ISAT that only a surface layer 10–15 mm thick is tested (page 191) surely depends on the concrete? Work at UWIST[25] has found that, apart from some concretes which were very susceptible to initial curing, where percolation[26] was evident at 50 mm depth from the test surfaces of 100 mm cubes, penetration depths of 30 mm and more were seen on splitting the specimens immediately after testing.

Another aspect which may be important is the density gradient in concrete. As well as the normally expected gradient in the vertical direction (i.e. the casting direction) there is a porosity gradient, certainly in small test specimens and perhaps in the in situ concrete, horizontally inwards (i.e. at right angles to the casting direction). Table II shows some data on water accessible porosity for two of the concretes from Table I. Porosity is defined as the volume of water absorbed under vacuum saturation with respect to the bulk volume of the specimen. Prisms 76 × 76 × 254 mm were sawn longitudinally in layers nominally 10 mm thick and each layer was further sawn into four pieces as shown in Figure V. The porosity was determined for each piece and the mean and standard deviation of each set of four, per layer, is given in Table II. There is a significant difference in porosity between the surface and fourth layers, the trends being typical of values found in the many specimens tested for different concretes. This therefore confirms Kreijger's work and is an indication that a porosity gradient should be taken into account when testing flow through the surface. The authors point out (page 191) that the Figg test measures mainly the quality

TABLE I: **ISA values for some OPC and OPC/pfa concretes subject to air drying*.**

OPC content (kg/m^3)	Pfa content (kg/m^3)	Nominal water content (kg/m^3)	Curing history	ISA (10^{-2} ml/m^2/s)		
				10 min	30 min	1 h
330 231	– 99	170 170	7 days in air	12 22	5 11	2 5
330 231	– 99	170 170	1 day in water then 6 days in air	10 13	4·5 6·5	1 1·5
450 315	– 135	165 165	7 days in air	8·5 13	3·5 6	0·5 2·5
450 315	– 135	165 165	100 days in air	14·5 20	6·5 10	2 5·2

*Air drying was at 20°C and 68% RH immediately after demoulding at 1 day, apart from that water-cured for 1 day.

TABLE II: **Water-accessible porosity of surface layers of an OPC and an OPC/pfa concrete.**

Layer*	Mean porosity (% of volume)		Standard deviation (%)	
	OPC mix	Pfa mix	OPC mix	Pfa mix
1 (0–10 mm)	12·8	15·5	0·15	0·38
2 (10–20 mm)	9·7	12·8	0·27	0·19
3 (20–30 mm)	8·3	10·9	0·05	0·09
4 (30–40 mm)	7·5	8·9	0·55	0·10

*See Figure V for position of layers.

of the inner cover-crete and thus is less influenced by the surface layer. The proposed CAT is clearly an improvement on that but what effect, if any, do they think the porosity gradient will have on the observed absorption?

Perhaps the more fundamental question is: how valid is any test which, however good as a test (acceptable sensitivity, reproducibility and so on), affects the concrete in a basic way which may interfere with the nature of the phenomenon being checked? The drilling of a hole, apart from potential damage right at the location where fluid penetration commences, of small diameter, which then allows flow roughly parallel to the surface could be seen as essentially different from the application of fluid pressure to the surface itself.

The authors draw attention to carbonation and to surface coatings; but if these, in practice, form part of the concrete 'skin' are they not then important contributing factors affecting the penetration of fluid into the concrete? What is the object of the test, to measure some aspect of the porosity or pore structure of a concrete sample, or to assess some important aspects of in situ concrete reacting with its environment?

It is important that in situ performance of concrete is monitored non-destructively and more or less continuously over a reasonable time, not least because of the role of the changing moisture content. This is a challenge which will probably be met sooner rather than later provided that care is exercised in devising appropriate monitoring systems. The authors deserve great credit for publishing extensive experimental data which have properly prompted questions and which will help to ensure progress towards the successful meeting of the challenge.

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Contribution by M. Levitt

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The authors have collated a lot of useful information which, amongst others, will be useful to the British Standard Committee dealing with the revision of BS1881: Part 5, Section 6 (to become Part 208). However, although the term 'in situ' is used in the title, the technical and contractual conditions that apply to site testing do not appear to have been considered in depth. There are also several technical aspects that lack a full description and I offer the authors the following points for their response.

Concerning the manufacture of the concretes for the ISA tests the description and tables lead to confusion over the regimes used, since times are omitted and one does not know when the 48 h water immersion occurred. Furthermore, although the photographs show cylindrical specimens, there is no reference to their size, casting or coring preparation and which face (cast or cored) was the test face.

On the ISAT test procedure there is no reference in BS 1881: Part 6 to the purity of the water. With relatively young concrete this is felt to be largely irrelevant as once water makes contact with fairly new concrete it will become a lime solution. Provided that the water is clean this is really all that matters.

The authors also make a reference to model aircraft elastic being like an elastic band. Most of the elastic is about 4·5 mm square section. BS 1881: Part 6 does not refer to "rough surfaces" when comparing a clamped gasketted cap. On site it is a different matter and a Virendeel or similar shaped cap is ideal. The data produced comparing these two assemblies on virtually identical concretes only shows a significant increase in variability at 10 min. This could be due to a variety of reasons such as initial hydrostatic pressure causing the sealant to creep slightly or water getting into and filling small voids in the sealant just under the knife edges.

The data on conditioning is extremely valuable for laboratory comparison but loses sight of two factors:

(1) A strict drying regime in the laboratory will give ISAT data indicating the maximum potential for surface absorption.

(2) However, on site, the average moisture content is about 8% by mass in exposed conditions (about 3% by volume) and one has to test damp concrete on site as its resistance to further durability risks is largely a factor of the resistance already there due to the presence of water.

This point has been borne in mind in arriving at site specifications and that is why the limits referred to in the authors' Reference 7 appear to be very low.

The comments about the parameter *n* in the ISA equation varying from 0·3 to 0·7 not being due to flushing and silting mechanisms respectively are acceptable. Although most of my work was relevant to hammer-compacted cast stone and may not necessarily be related to vibrated wet-cast concrete it needs to be borne in mind that the ISA equation is empirically derived from Poiseuille's equation which is also empirical. It is fortuitous that the authors, the writer and many other researchers have found a log/log linear relationship between the ISA and time for a large range of concretes. A study of the mechanisms causing *n* to vary from 0·3 to 0·7 would constitute a large research project with resulting data unlikely to be of more than academic interest.

The authors discuss the variability of the various test methods on replicate tests of the same concrete. Concrete is a highly variable material and adjoining areas may be seen to be wetting and drying out at different rates during natural weathering. It thus becomes suspect if one produces three ISA, Figg or CAT results from the same concrete within close limits. What is really important is to examine how variable the concrete surface is and the durability significance of the worst of the results or all the results. After all, it is possible, for example by differential curing conditions, to produce a section of concrete where one part of it will have significantly reduced durability characteristics and other parts will have a high resistance.

The conclusions in the paper are fully endorsed and I, like many other readers, look forward to reading more about the index values and durability behaviour.

Contribution by J. Figg

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The authors are to be congratulated on the very considerable amount of work reported in this paper and on the thorough comparisons between the various methods.

Concerning the variability reported for the test results for air permeability, it appears that Dr Dhir and his colleagues only used single test holes in each concrete specimen, so their results include inter-specimen variability as well as the variability of the test itself. We have found that it is better to evaluate the means of at least three and preferably six holes in each sample, which has resulted in a coefficient of variation of 12–15%. Our specimens have been dried at 50°C (to less than 1% change in mass per 24 h) since drying at a higher temperature appears to cause damage to the cement paste pore structure and consequent greater apparent permeability, as illustrated in Figure 11 in the paper, for example.

The Figg test purposefully ignores the outermost few millimetres of concrete surface since, whether off-the-shutter or textured, it is significantly different from the main cover concrete and the test is intended to give a measure of the protective quality of the concrete surrounding embedded reinforcement. It is noted that the authors used three sizes of test hole but we still consider that holes 10 mm in diameter and 40 mm deep are the most satisfactory compromise for routine use on site, for both the water and air permeability test.

Since we reported improvements to the original Figg method in 1984 (Reference 20 in the paper), we have gained considerable experience of the use of the method on structures and a number of other workers have also been using the apparatus. The test results

TABLE III: **Figg air and water permeability values for concretes of varying protective quality.**

Concrete category	Protective quality	Air permeability		Water permeability
		Time (s)	AER* value (s/ml)	Absorption rate (s/ml × 10^3)
0	Poor	< 30	< 8	< 2
1	Not very good	30–100	8–25	2–5
2	Fair	100–300	25–75	5–10
3	Good	300–1000	75–250	10–50
4	Excellent	> 1000	> 250	> 50

*Air Exclusion Rating.

have been used to justify retention of concrete as well as to detect concrete of poor protective quality.

No evidence has been obtained to date for amendment of the quality criteria published in MCR 129, but additional work has indicated that a quantitative measurement of the resistance of concrete to the inflow of air would aid comparison of results. From the volume of air required to cause the 5 kPa change in pressure an 'Air Exclusion Rating' (AER) can be calculated. Table III shows AER values together with the better-established 'Figg times' and also quantitative values for the water permeability test.

Reply by the authors

We would like to thank Messrs Lydon and Al-Odaallah, Dr Levitt and Mr Figg for the interest they have shown in the paper and their detailed comments on and discussion of the results presented therein. In order to deal with all the points raised we respond separately to their contributions.

To Messrs Lydon and Al-Odaallah
Their comments are confined mainly to the ISAT results and we will deal with them in the order they have been raised.

Para 2. The E3 cured specimens were used to study the effect of moisture content on the measured ISA and the authors apologise for this omission in Figures 2 and 3. The curing conditions used for the results reported in Figure 5 were as stated therein, i.e. the specimens were subjected to initial water curing varying from 1 to 28 days, with all the specimens then stored in water at 20°C for 48 h before preparing them for ISA testing, as stated on page 184. The variability of ISA measurements taken at different intervals up to 120 min was essentially similar (Table IV), and this was confirmed by the control test data obtained throughout the duration of the study (Table V). The ISA results at different times showed a similar relationship with the nominal strength of concrete (Figure VI). However, the 10 min ISA measure was chosen as the principal measurement for a number of reasons, the most important of which are: (1) the speed with which the results can be obtained which directly reduces the cost of testing, particularly for in situ testing, and (2) the sensitivity of the response over a given change in the quality of concrete (Figure VII), in particular of concretes with low to medium strength; these are often more vulnerable to deterioration and are representative of typical grades used commonly in concrete construction. Moreover, it has to be remembered that the ISAT is an arbitrary, but practical, test, the meaningfullness of which is more apparent the shorter the time at which the test is carried out. The authors consider 10 min ISAT a workable compromise.

TABLE IV: **Within-batch variability of ISAT results for concrete with water/cement ratio 0·55 and curing condition E3.**

Concrete mix batch number*	Coefficient of variation of ISA results (%)				
	Test time (min)				
	10	20	30	60	120
1	5·7	5·7	5·5	5·3	5·0
2	4·2	4·2	4·9	3·1	3·6
3	5·0	5·4	5·2	5·7	5·0
4	6·0	6·2	5·4	6·0	5·0
5	7·5	7·1	7·1	6·6	5·4
6	6·3	5·7	4·7	5·8	5·8
7	4·0	4·1	4·5	4·0	4·8
8	3·8	3·6	4·0	1·9	2·8

*Each batch consisted of 10 test specimens.

Para 3. The authors accept the point made with regard to the lack of consensus on the choice of relative humidity for testing concrete. In fact the actual relative humidity can vary within a humidity chamber and

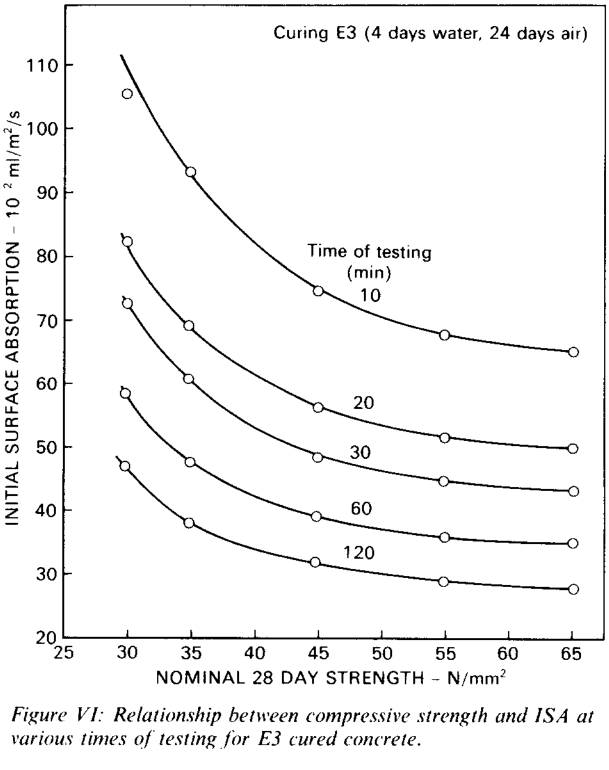

Figure VI: Relationship between compressive strength and ISA at various times of testing for E3 cured concrete.

TABLE V: Control ISAT results taken at regular intervals over a period of 3 years for concrete with water/cement ratio 0.55 and curing E3.

Test specimen number	Initial surface absorption × 10^{-2} ml/m²/s				
	Test duration (min)				
	10	20	30	60	120
1	73	55	47	36	29
2	73	55	48	39	30
3	69	51	45	36	29
4	81	60	52	41	32
5	82	60	51	41	32
6	78	58	50	40	32
7	79	59	51	40	32
8	84	62	52	42	33
9	73	54	46	37	30
10	80	59	50	40	32
11	69	52	44	36	29
12	70	53	45	36	29
13	70	51	45	36	28
14	76	58	50	40	32
15	73	58	47	36	29
16	81	58	50	40	31
17	82	60	51	40	32
18	73	55	48	36	29
19	72	53	45	38	30
20	79	60	51	42	33
21	77	58	51	40	33
22	76	57	49	38	30
23	78	57	49	39	31
24	81	58	49	39	30
25	74	56	48	39	31
26	82	62	52	40	31
27	80	59	54	41	33
28	79	59	52	40	31
29	82	61	52	39	32
30	79	59	51	40	31
31	75	57	49	38	30
32	79	59	53	41	33
33	79	59	52	41	33
34	70	52	46	36	29
35	76	60	51	42	34
36	74	59	51	41	33
$\bar{x}$	77	57	49	39	31
SD	4·3	3·0	2·7	2·0	1·6
V%	5·6	5·3	5·5	5·1	5·2

*Each batch consisted of 10 test specimens.

from that recorded with the commonly used instruments. A relative humidity of 55% was chosen as being close to a middle value, and was considered sufficient in this case, particularly in the light of the variations in relative humidity encountered in the UK and worldwide. Moreover, this relative humidity was though not to alter unrealistically the response of concrete to the ISAT.

TABLE VI: Changes in the ISAT values of concrete (water/cement ratio 0·4 and E3 curing condition) with time, using different preconditioning methods.

Time from first reading (days)	10 min ISAT × 10^{-2} ml/m²/s		
	Drying method*		
	D1	D2	D3
0	63	34	7
5	64	42	8
10	60	44	10
15	61	48	10
20	62	50	11
30	–	47	12
50	–	48	11
75	–	–	14
100	–	–	14

*Drying methods:
D1 weight change less than 0·1% over 24 h (6 days drying)
D2 weight change less than 0·1% over 24 h (9 days drying)
D3 2 days drying

Paras 4, 5, 6. The structure of concrete changes with time. These changes are governed by many intrinsic and extrinsic factors and they are most marked at early ages. It also follows that it is impossible to condition concrete without giving rise to some subsequent effects on the property measured. Thus it is important that such effects are recognized, carefully considered and judged to be acceptable. The authors have been mindful of these factors and came to the conclusion that under laboratory conditions the use of conditioning at 105°C is preferable to any other lower temperature (Table VI). Furthermore, intrinsic

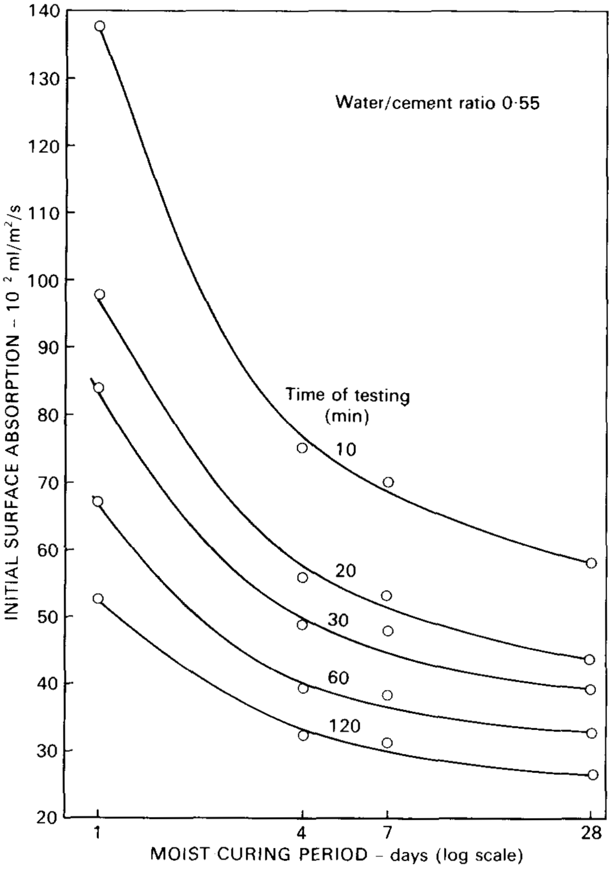

Figure VII: Relationship between ISA measured at various times and moist curing period for concrete with water/cement ratio 0·55.

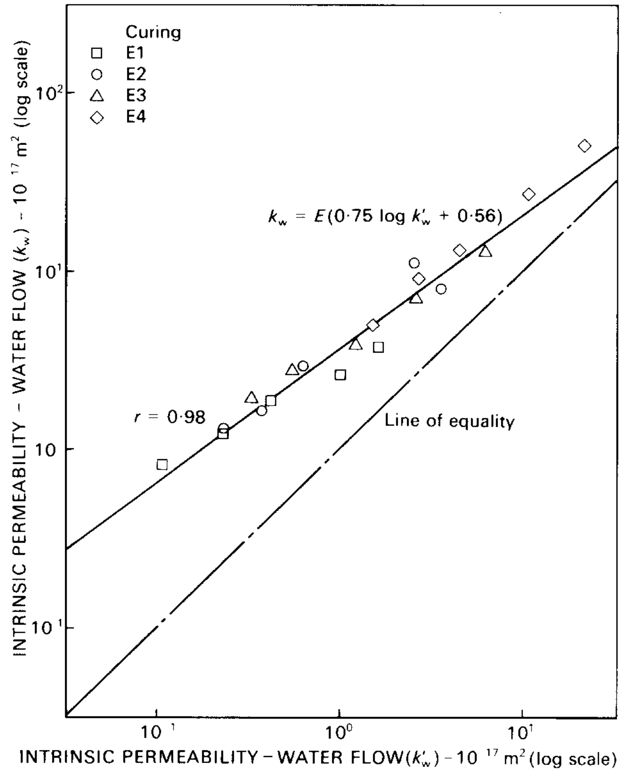

Figure VIII: Relationship between k_w and k'_w when the specimens are dried at 105°C and 20°C respectively before vacuum saturating them for permeability tests.

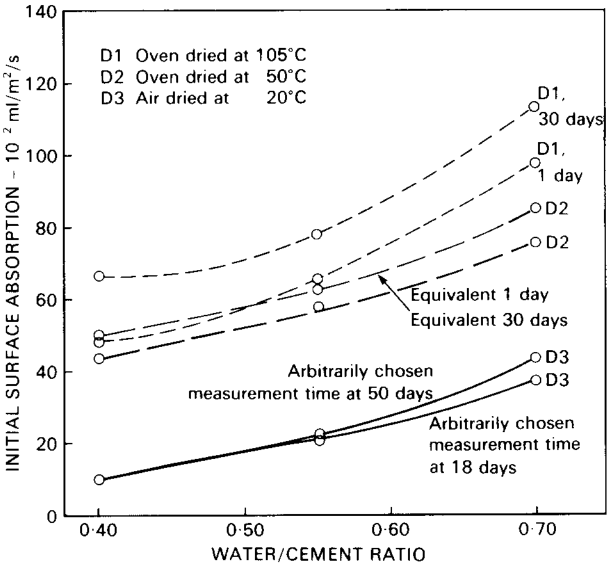

Figure IX: Relationship between initial surface absorption and water/cement ratio of concrete dried at different temperatures.

permeability tests carried out using water, which will be fully reported in our next paper, showed clearly that a good correlation exists between the measurements made on concrete specimens conditioned at 105°C and 20°C temperatures (Figure VIII).

Para 7. Our comments on page 184 have been misunderstood and misinterpreted. The point is made that the decay parameter n which is used in the theoretical derivation of ISA does not appear to be sufficiently sensitive to indicate the absorptivity of concrete over a wide range of strengths, 30 to 65 N/mm^2, and water/cement ratios, 0·70 to 0·40, (Table 1) and subjected to different initial moist curing E1 to E4, including air at 20°C and 55% RH (Table 2). These comments are supported by the corresponding n values obtained with the other drying conditions used in the study (Table 3).

Para 8. As stated in the paper, the moisture content of a concrete can affect the ISA measurement greatly (Table VI). Thus for a realistic comparison of ISA results for a range of concretes in term of strength, water/cement ratio or cement content, with specimens prepared at different conditioning temperatures (Table 3), the moisture content of the test specimens must be essentially the same. For the results reported, the only appropriate course of action would be to start with an ISAT using a moisture level equivalent to that obtained after 1 day of drying at 105°C. The corresponding times needed to achieve this condition for E3 cured concrete were found to be between 10 and 15 days at 55°C and over 100 days at 20°C. The results are shown plotted in Figure IX and the trends depicted therein are self-explanatory. The authors think that a method along the principles discussed by Parrott[(24)] to achieve a desired moisture condition within concrete is not likely to be satisfactory with the size of specimens required for ISA measurements. Thus, with the present options, drying at 105°C is probably the best conditioning method for ISA measurements of concrete under laboratory conditions.

Para 9. Clearly the aggregates can have considerable influence, as was found to be the case when lightweight aggregates were used in this study (not reported in the paper). Although the authors have not tested any other types of aggregate, it is thought that most of the commonly used natural aggregates (crushed rock or gravel) can be divided into a few groups based on their water absorption values and this factor can then be used to interpret ISAT results to judge the durability potential of concrete.

Para 10. Whilst not disagreeing with the statement that calls for rigorous work to understand in situ concrete behaviour, it must be recognized that such an understanding has tended to evolve gradually as experience is gained. Meanwhile, a preliminary engineering judgement has to be made to provide some guidance. It is for this reason that the authors have attempted to apply the results obtained to examine the appropriateness of the various recommendations on curing concrete which are listed in Table 4. The relationships with the in situ concrete have been developed for similar reasons in order to permit some relative assessments to be made. In the real world, there is little point in forcing a black or white approach to concrete.

Para 11. Messrs Lydon and Al Odaallah have used the values of coefficient of variation in Table 6 to calculate back to the corresponding values of standard deviation. However, if, as in this case, there are varying mean values of the data population in each group it is statistically inappropriate to use standard deviation to establish the significant difference between the variability of different groups of results. The other important point is that in standardizing the ISAT procedure the specimen size effect must be minimized and therefore it is not the different mean ISA values which are the real issue in this instance, but instead, as stated in the paper on page 188, that in order to minimize the size effect a minimum distance of 30 mm is required between the edge of the specimen and the internal circumference of the cap.

Para 12. The comments on page 187 of the paper were based on the corresponding concrete mixes, with and without pfa, designed to have equal workability and 28 day strength. But the results given by Messrs Lydon and Al-Odaallah in their Table I are for the mixes where both these requirements were not met. In such a case the two sets of concretes are not comparable(27). However, the results in Table I are interesting and make two important points: (1) for the mixes with a total cementitious content of 300 kg/m^3 1 day water curing after demoulding has produced, on average, an improvement of 124% and 43% in the ISA values of pfa concrete and OPC concrete, respectively, and (2) for the mixes with a total cementitious content of 450 kg/m^3, extending the air curing from 7 days to 100 days has produced, on average, a deterioration of 78% and 152% in the ISA values of pfa concrete and OPC concrete, respectively. This suggests that pfa concrete responds more favourably to initial moist curing and suffers less deterioration during prolonged dry air exposure. In other words this work showed no adverse property as a result of using pfa.

Para 13. The penetration of water into concrete during an ISAT will depend both on the quality of concrete and the duration of test. All other things being equal, the surface of concrete to approximately 10–15 mm depth will play the dominant role in influencing ISA measurements, not least because the greater the depth of concrete under test the more difficult it is to control the flow.

Para 14. The density gradient or more appropriately the quality gradient across a concrete member section, both in the direction of casting and at right angles to it, is important. In fact, this quality gradient was the key factor in initiating the research, part of which has been reported in this and a previous paper(6). The authors were also familiar with the study reported by Kreijger(3). The main distinction between the Figg water absorption and CAT (apart from different reliabilities of the results obtained) is that in the former the test hole is plugged to 20 mm depth from the concrete surface and therefore the influence of the near-surface concrete is minimal, whilst in the latter the concrete layers to 50 mm depth and up to say 15 mm beyond are measured in the absorption values recorded.

Para 15. From considerations of durability, the quality of concrete up to the reinforcement (covercrete) assumes the greatest importance. The ISAT is essentially a surface test only and the CAT has been developed to overcome this limitation. Although the damage caused by drilling the test hole will influence the measured absorption values we were unable to come up with a solution to this problem and would have welcomed any suggestions in this regard. However, we would say that our recommended hole size and test procedure have produced sufficiently reliable results to be able to assist in an engineering judgement.

Para 16. The carbonation of surface concrete or application of surface coatings to improve curing will alter the value of permeation properties measured from the surface, such as in the ISAT. Thus, it would always be advisable to remove surface coatings before ISA measurements are made. However, although a thin layer of carbonated concrete reduces the measured ISA significantly, it does not improve the carbonation resistance of the inner cover concrete. To overcome this difficulty in the quality assessment of concrete it would be desirable to use the CAT, thus minimizing the influence of the carbonated layer.

To Dr Levitt

We recognized that the use of term ‘in situ’ in the title of the paper might cause some concern. Nevertheless, after careful consideration, it was decided to be appropriate to retain it, because, as stated in para 5 on page 183, the paper deals with test methods which have been claimed to be suitable for in situ testing of concrete. The paper also makes it clear that one of the main aims of the study was to investigate thoroughly the potential capabilities of the methods described, albeit under ideal laboratory conditions.

Dr Levitt’s comments are confined to ISA testing and he has raised many helpful queries. It should be noted that for the bulk of the work reported in the paper 150 mm cubes were used as the test specimens and the ISAT measurements were made centrally on the side faces of the cubes as cast. As stated in para 2 on page 184, at the selected test age all the specimens were soaked for 48 h before drying them (Table 3) for testing. The test age was mainly 28 days and this has been stated with some of the Figures, though it could have been made clearer. De-ionised and de-aired water was used in order to minimize the number of test variables, but the authors accept that in practice clean tap water would suffice for ISA testing.

The authors appreciate the distinction made by Dr Levitt between the laboratory and on-site conditions. It was precisely for this reason that we wanted to establish the variations that may appear in the ISAT results due to the presence of varied moisture in the test concrete. Indeed the paper highlights the shortcomings of the BS 1881 test conditions in this regard. The issue here is not the expediency but the confidence with which ISAT can be effectively used in practical terms. Whilst a low, medium or high test number may be acceptable as an index value, the reliability of any such number is of paramount importance and the paper, on page 194, suggests that the on-site concrete preparation procedure for the ISAT to BS 1881 can lead to variable and misleading results.

The authors agree with Dr Levitt's comment with regard to the time consuming studies of the mechanism causing n to vary. However, our discussion on the n value was meant to show its insignificance in studying the absorptivity characteristics of concrete.

To Mr Figg

Mr Figg's comments are confined to the use of the apparatus he originally developed(8) and subsequently improved upon in 1984(20).

One of the most important factors in determining the suitability of a test is the reliability of the results obtained. This was indeed one of the main features of the reported investigation and it was rigorously determined. The authors therefore stand by their recommendations on hole size (13 × 50 mm), vacuum pressure range (0·055 and 0·045 N/mm^2) below atmospheric pressure) and additionally the specimen drying temperature (105°C) when tested in the laboratory. The on-site use of the apparatus was carefully considered and it was thought that the recommended test hole size can easily be formed and be usefully employed to achieve more reliable results.

The authors also see no meaningful difference, within the laboratory conditions, between using a number of small specimens (making one test per specimen) and a single large specimen (making a number of tests) prepared from the same batch of concrete. Thus, it is felt that the reported information on the test variability based on within-batch and between-batch tests is of the right order.

Cover concrete includes the top 20 mm as well as the layer immediately surrounding the embedded reinforcement. The outermost surface concrete, which may be significantly different from the rest of the cover, makes a contribution to the protection of reinforcement and cannot be ignored. This layer of concrete is also significant to the aesthetic value of the structure. Thus, the authors have taken the view that the surface layers of concrete should be included in the measurement of its permeation characteristics.

REFERENCE

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