# USE OF SORPTIVITY AS A GUIDE TO CONCRETE DURABILITY PERFORMANCE

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## SUMMARY

As a simple index test for characterising the durability of a particular concrete, the measurement of sorptivity has a number of advantages. The test method is analogous to a recognised deterioration process in the field, does not require specialised equipment, and yields relatively rapid results even when considering high performance concrete. However, obtaining meaningful data is dependent on preconditioning the concrete to a consistent and reproducible internal moisture state, which is not necessarily a simple task. This paper reviews currently suggested methodologies for sorptivity testing, including the necessary sample preparation. It also presents experimental data which examines the sensitivity of the sorptivity test to variations in concrete quality due to factors such as composition and curing.

## WATER TRANSPORT IN CONCRETE

For many deleterious processes, the durability of concrete is intimately connected to the ease with which water is able to percolate through it. This has traditionally been characterised by *permeability*, the rate of water flow through saturated concrete under an applied pressure gradient. The technique has some attraction; permeability is an intrinsic material property defined by a well-understood physical theory, but this advantage tends to be outweighed by less favourable considerations. These include both the practical – modern high-performance concretes have permeabilities so low they are difficult to measure accurately – and the theoretical – the high pressure test conditions are not analogous to those experienced by most ‘real-world’ concrete structures.

Hydraulic *sorptivity*, first applied to building materials by Hall [1], offers an alternative measure of fluid transport properties of concrete. As the name suggests, it characterises the tendency for a dry, or partially saturated, porous material to absorb water via capillary action. For most structures, which do not become routinely water-saturated, capillary effects are likely to be the dominant transport process. Thus sorptivity is a more appropriate parameter for categorising concrete performance than permeability.

## SORPTIVITY THEORY AND PRACTICE

Sorption occurs when water is drawn through the interior of the concrete by capillary forces. These arise from the surface tension of the liquid in contact with the walls of the concrete’s capillary pore network. For the simplest case of one-dimensional flow through a plane surface, the water ingress is given by the equation [2]:

$$M_{(t)} = \rho A S \sqrt{t} \qquad (1)$$

where $M_{(t)}$ is the mass of liquid in grams that has been absorbed after time $t$, $\rho$ is the density of the fluid (neglected for the case of water since $\rho = 1.0$ g/cm$^3$ under normal ambient conditions), $A$ is the surface area in mm$^2$ being exposed to the invading liquid, and $S$ is concrete’s *Sorptivity Coefficient*, which has units of mm/min$^{½}$.

Equation *(1)* forms the basis of a typical sorptivity experiment, which is shown diagrammatically in ***Figure One***. Regular prismatic concrete specimens are initially preconditioned by drying to some reproducible moisture state. After cooling they are weighed, then placed in a tray of shallow water and supported such that one face is immersed to a depth of 2 – 3 mm while allowing the water free access across the entire wetted face. At regular intervals the specimens are lifted out, patted with a damp cloth to remove any adhering water droplets, and weighed to an accuracy of 0.1 g or better. At the conclusion of the test, the gain in mass of the specimens at each measured time interval is divided by the area of the exposed place and plotted against the square root of time, as shown in ***Figure Two***.

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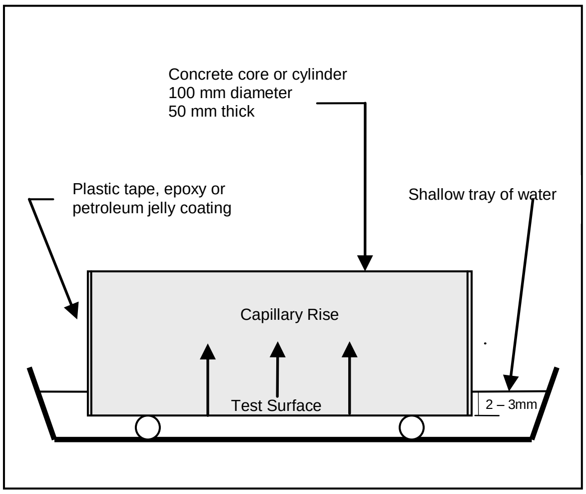

***Figure One:*** *Usual arrangement for a sorptivity test.*

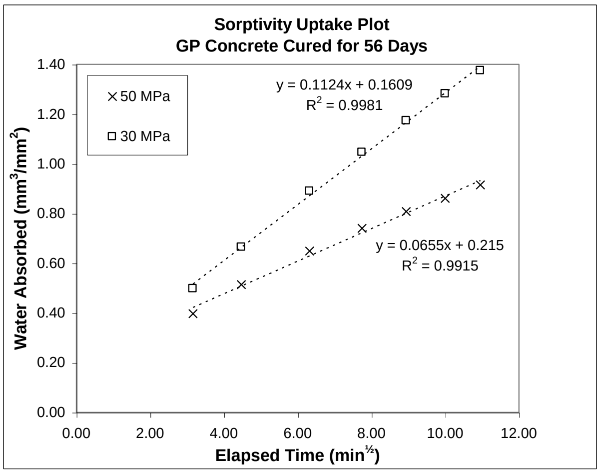

***Figure Two:*** *Typical sorptivity results for two different grade concretes.*

The result should be a straight line whose gradient, determined by least-squares linear regression, defines the Sorptivity Coefficient of the concrete. Ideally, the linear regression coefficient obtained during the curve fitting procedure should be > 0.98 [3]. Plots which show systematic curvature cannot be used to calculate sorptivity. This situation is comparatively rare but incidences of downward curvature have been associated with materials with coarse pore structures (e.g. concrete masonry) in which the capillary forces are weak and comparable with the gradients of gravitational potential [4]. Curvature may also occur in cases where the preconditioning of the test specimen has produced non-uniform moisture distributions within the concrete.

Sorptivity plots typically show a small positive intercept on the y-axis. This is interpreted to be due to initial filling of pores on the exposed inflow surface and sides of the specimen [4]. For this reason, the initial datum point (the mass uptake between t = 0 and the first weighing) is normally ignored in the calculation of sorptivity.

Sorptivity measurements are usually made over comparatively short periods; Hall [4] suggests two hours is sufficient. It has been claimed [5] that mortars and concretes are characterised by two Sorptivity Coefficients, represented by a distinct break in gradient on the sorptivity uptake plot. The later-age Sorptivity Coefficient, for times longer than one day, is attributed to phenomena other than the suction due to the capillary pore network, such as the slow filling of air voids and interactions of the water with cement gel.

Within this broad outline, many variations in the test procedure are possible. For example, a small moat can be built on top of the specimen such that the invading fluid is in contact with the top of the specimen. Under this scheme ("ponding sorptivity"), the capillary forces act in concert with the gravitational potential, which may be a more realistic simulation of certain situations (e.g. water on a pavement or bridge deck).

Some investigators [6] prefer to measure the depth of liquid penetration directly rather than monitor the change in mass. This requires the destructive splitting of the sample at the end of the test and a direct measurement of the penetration front (i.e. the height to which the concrete is "wet"). The sorptivity equation then becomes:

$$d_{(t)} = B\sqrt{t} \qquad (2)$$

where $d_{(t)}$ is the depth of penetration after time t and *B* is the *Penetration Coefficient*. Note that the units of B are length/time$^{½}$ as with the Sorptivity Coefficient, although they are numerically quite different quantities. This can be a cause for confusion.

BRANZ does not favour direct determination of Penetration Coefficients because of the difficulty in precisely identifying and measuring the penetration front. The reliance on a single measurement without the benefit of being able to improve precision by fitting the Sorptivity Coefficient to multiple data points, would seem to negate one of the advantages of the test, which is its surprising sensitivity to small changes in concrete quality. However it is conceded that the Penetration Coefficient *(B)* is conceptually easier to understand than the Sorptivity Coefficient *(S)*, because it gives the rate of advance of the wetting front directly. The Sorptivity and Penetration Coefficients are theoretically related by the effective porosity of the concrete:

$$Effective \cdot Porosity \approx \frac{S}{B} \qquad (3)$$

This provides an approximate conversion between the values, but it should be noted that the porosity required is that which would be filled by capillarity. This volume would not include entrapped air voids and thus may differ from the porosity determined by an absorption test. This difference in definition makes direct comparisons of data from each test method uncertain.

## ADVANTAGES & DISADVANTAGES

The primary advantages of the sorptivity test described can be enumerated as follows:

1. Sorptivity requires no specialised equipment beyond a suitably accurate balance and stopwatch.
2. With a logical weighing sequence in place, multiple specimens (say 10 to 20) can be tested at the same time.
3. The test uses a mechanism relevant to actual deterioration processes in field concrete.
4. The test is sensitive to the overall interconnectivity of the concrete's pore network. In contrast an absorption test such as AS1012.21 [7] is more sensitive to total pore volume, a property more critical to strength than durability.
5. A well-developed mathematical framework is available for capillary flow in unsaturated materials which unites both sorptivity and permeability, and makes explicit their dependence on the water content of the material.

Consideration of unsaturated flow theory reveals the largest difficulty in the practical application of sorptivity: For a given porous material, sorptivity is found to be strictly a function of the initial and final moisture contents of the test material, $\theta_0$ and $\theta_1$ respectively

$$S = \int_{\theta_0}^{\theta_1} \phi d\theta \qquad (4)$$

where Φ gives the dependence of the moisture content on time and position in the sample [4].

As a consequence of equation *(4)*, it is necessary to define a reproducible internal moisture state $\theta_0$ to which test specimens can be conditioned prior to commencing a sorptivity test (the final state $\theta_1$ is described unambiguously by contact with the invading liquid). It is also necessary to ensure that the moisture distribution is even throughout the specimens. This cannot be taken for granted as steep near-surface moisture gradients are a known feature of capillary drying [8].

## CURRENT USE & NEEDED RESEARCH

For a number of years BRANZ has used sorptivity testing as a simple durability index to rank the performance of concrete mixes. This is the second of the three main tasks required for assuring the long-term durability of a new concrete structure, viz:

1. Define the service environment and performance requirements for the structure.
2. Optimize the concrete mix design in the laboratory by characterising the performance with appropriate index values.
3. Test the in-situ concrete to ensure that the required index values have been achieved in practice.

(after Alexander and Ballim [9]).

BRANZ' experience has given us confidence that sorptivity is a useful test, both reproducible and correlating as expected with mix composition and curing. This suggests that its role could be extended from a laboratory tool (step 2 above) to include use as a quality assurance test (step 3). For example, this might include incorporation in a construction specification as an adjunct to compressive strength, or employing the test to determine the effectiveness of site curing.

For this to occur however, it is necessary for a considerable database of sorptivity results to be compiled to allow realistic minimum specifications to be set. In particular, sorptivity values for high performance concrete, comparisons of the influence of different conditioning regimes on the quality of the sorptivity test results, and an assessment of the differences that could be expected between 'labcrete' and field concrete, do not appear to have been adequately addressed. BRANZ is currently engaged on an experimental programme that aims to resolve some of these issues.

## EXPERIMENTAL PROGRAMME

This phase of the experimental programme has concentrated on evaluating the practicality of different sorptivity preconditioning methods, and their impact on the effectiveness of the test as a discriminator for degree of curing.

A series of five 100 mm thick concrete slabs were cast into form-ply boxing, compacted with a poker vibrator, and hand-trowelled. The concrete used was a 30 MPa laboratory-produced mix, made with GP cement and Wellington crushed aggregates, and intended to be reasonably representative of a ready-mixed structural grade concrete. The mix design is given in ***Table One***. A set of standard test cylinders were also moulded at the same time.

| Mix Constituents | | per $m^3$ |
|---|---|---|
| 19 mm | Belmont Chip | 638 kg |
| 13 mm | Belmont Chip | 426 kg |
| Sand | Puketapu | 860 kg |
| GP Cement | Golden Bay | 290 kg |
| Water Reducer | Sika BV50N | 0.7 l |
| Total Water | | 175 l |

***Table One:*** *Concrete mix proportions.*

After 24 hours protected from water loss by black polythene, the slabs were stripped from their formwork. The first slab was allowed to dry immediately in a controlled environment room at 21°C and 65% RH. The remaining four slabs were moved to a 'fog room' maintained at 100%RH and allowed to cure for 3, 7, 28 and 56 days respectively. At the conclusion of its allocated curing period each slab was placed in the drying room, joining those removed earlier. Once the 56-day slab had completed curing, all of the slabs were cored with a 100 mm diameter coring bit to provide specimens for sorptivity testing. Twenty-five cores were taken from each slab allowing for five replicate sorptivity tests using four different conditioning procedures at each curing time. A series of 50 mm cores were also taken to determine the actual (dry) compressive strength of each slab. All of these cores were tested at 68 days after casting.

The sorptivity specimen cores were trimmed to 50 mm thick for testing. Their orientation was chosen such that the water ingress surface corresponded to the cast face of the slab, both to mimic the likely situation in field concrete elements, and to minimise the influence of finishing technique on the sorptivity result. Concrete cast against a form face often demonstrates heterogeneity in the spatial distribution of the aggregate, with a layer of cement-rich paste at the surface [10]. To avoid the effect of this spatial variation on the test result approximately 8 mm was trimmed from the face of each core. Each suite of cores (sets of five test replicates cured at 1, 3, 7, 28 & 56 days) was then conditioned by one of the methods described below before their Sorptivity Coefficients were determined.

| Procedure | Pre-Conditioning | Conditioning | Post-Conditioning |
|---|---|---|---|
| **105°C Drying** | None | At 105°C in ventilated oven until $\Delta$mass < 0.1% / 24 hrs | Cool samples in desiccator. Test within 18 – 24 hours. |
| **50°C Drying** | None | As above but reduce temperature to 50°C | As above |
| **NIST Procedure** [11] | Vacuum saturate samples to SSD conditions.<br>Seal sides with tape to minimise formation of radial moisture gradients | Condition at 50°C & 80% RH for 7 days | Seal into container at 23°C.<br>Test when relative humidity in container stabilises |
| **RILEM Procedure** [12] | As Above | Dry sample at 50°C until:<br>$\Delta m = \frac{\theta_{SSD} - \theta_{65\% RH}}{1 + \theta_{SSD}} \cdot m_{sample}$<br>where:<br>$\Theta_{SSD}$=moisture content at SSD<br>$\Theta_{65\% RH}$=moisture content at 65% RH<br>Based on desorption experiments carried out under ambient conditions | Seal samples to prevent further moisture exchange.<br>Maintain at 50° for a minimum of 14 days |

***Table Two:*** *Comparison of conditioning procedures used*

### Conditioning Methods

As described earlier, the sorptivity of a concrete correlates strongly with its moisture content and internal relative humidity. All test samples therefore require some form of conditioning to achieve a uniform initial condition, regardless of whether they are saturated (e.g. test cylinders directly after curing) or have experienced some degree of drying. The features of the conditioning regimes chosen for the test programme are compared in ***Table Two***. All of the regimes were selected based on common usage in the literature.

The conditioning regimes can be subdivided into two groups, based on whether the aim is to produce an artificial 'dry' condition in the test specimens, or to replicate a moisture content typical of field concrete exposed to ambient conditions. Drying at 50º or 105ºC falls into the former category, the NIST [11] and RILEM [12] procedures belong in the latter.

Conditioning specimens at 105ºC in a ventilated oven until an equilibration of mass is achieved has been the norm, and many of the literature values for both sorptivity and permeability have been obtained with this technique. However, it has since been recognised that this temperature can alter the microstructure of the concrete, dehydrating the cement gel and inducing micro-cracking. For this reason BRANZ prefers to carry out the conditioning step at 50ºC. The disadvantage is that the end-point of the drying procedure is not clearly defined as at the higher temperature. By convention we chose to define the sample as dry when the weight loss over 24 hours is less than 0.1%. Once the specimens are dry they are cooled in a desiccator. The subsequent sorptivity testing normally takes place within 18 to 24 hours. It is assumed that the drying procedures are sufficiently aggressive to avoid creating any moisture gradients, at least in the near-surface concrete which influences a sorptivity test.

The NIST procedure, which has been submitted to ASTM for standardisation [3], requires test specimens to be conditioned in an environmental chamber maintained at 50 ± 2ºC and 80 ± 3% RH for 7 days. This is followed by a post-conditioning period of approximately 14 days duration in a sealed container at 23 ± 2ºC, during which the RH in the container is monitored. When the container humidity stabilises it is assumed that the moisture content of the specimens is uniformly distributed (no gradients) and in equilibrium with the measured RH. This should be in the range of 50 – 70%, which is similar to the internal humidity of concrete in field structures [13].

RILEM conditioning is a more complicated procedure which also aims to ensure initial moisture contents in equilibrium with natural ambient conditions. In addition to the regular sorptivity specimens, additional test concrete is prepared as thin (5 mm) slices or crushed into particles of equivalent diameter. Because of their high surface area, these samples will dry unassisted under ambient conditions relatively quickly. By doing this, the necessary water that must be removed to bring the larger test samples into equilibrium can be calculated. For absolute accuracy, this step must be carried out in a $CO_2$ free environment to avoid any change in mass associated with carbonation.

Once this weight loss has been determined, the drying of the actual test specimens can be accelerated at 50ºC. This is continued until the calculated loss of water has been attained to within a 5% level of accuracy, which necessitates frequent weighings over small time periods (hours to days). Subsequently, the specimens are sealed to prevent any further moisture loss and returned to the 50ºC environment for a minimum of 14 days. The elevated temperature should accelerate the redistribution of any spatial moisture gradient that has developed.

## RESULTS

***Figures Three to Six*** show the mean sorptivity results for each conditioning method, plotted as a function of the curing received by the test cores. The error bars shown are the 1 standard deviation limit calculated from the variability in the test replicates.

It is apparent that the Sorptivity Coefficients obtained under different conditioning regimes cannot be directly compared. Coefficients on concrete dried at 105ºC are approximately 1.5 – 2 times greater than those from the samples dried at 50ºC and more than 5 times greater than the results from NIST or RILEM conditioning.

Conditioning at 50ºC (***Figure Four***) appears to produce the most satisfactory result, with the Sorptivity Coefficients decreasing in a rational way as the curing period is extended. Statistical analyses (heteroscedastic t-tests) indicate that the differences between the coefficients are significant, that is, they represent a real change in concrete properties rather than random experimental uncertainty.

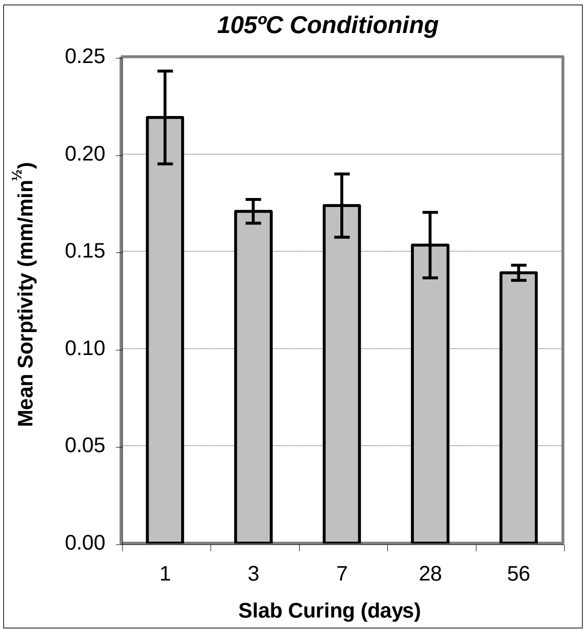

***Figure Three:*** *Mean sorptivity results for slab specimens conditioned by drying at 105ºC.*

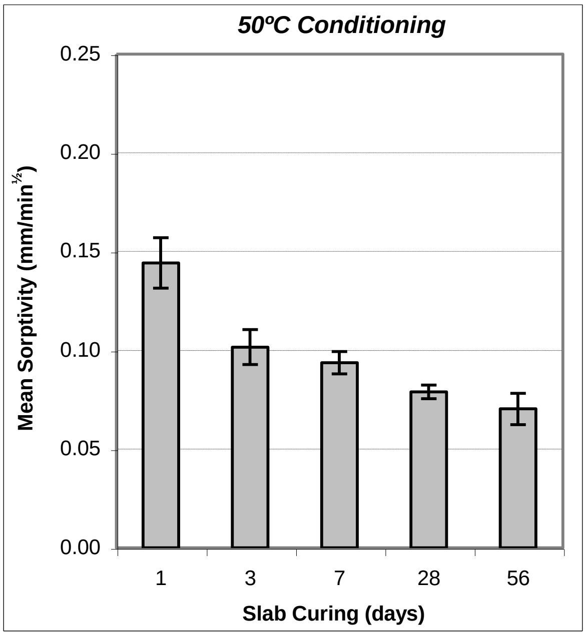

***Figure Four:*** *Mean sorptivity results for slab specimens conditioned by drying at 50ºC.*

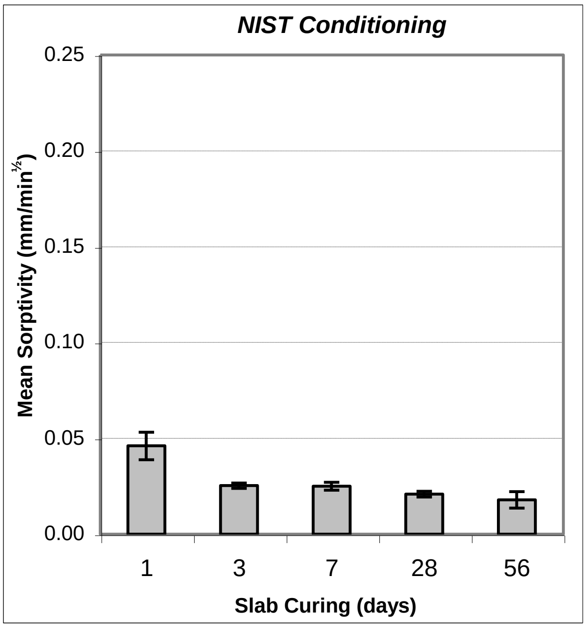

***Figure Five:*** *Mean sorptivity results for slab specimens conditioned by the NIST procedure.*

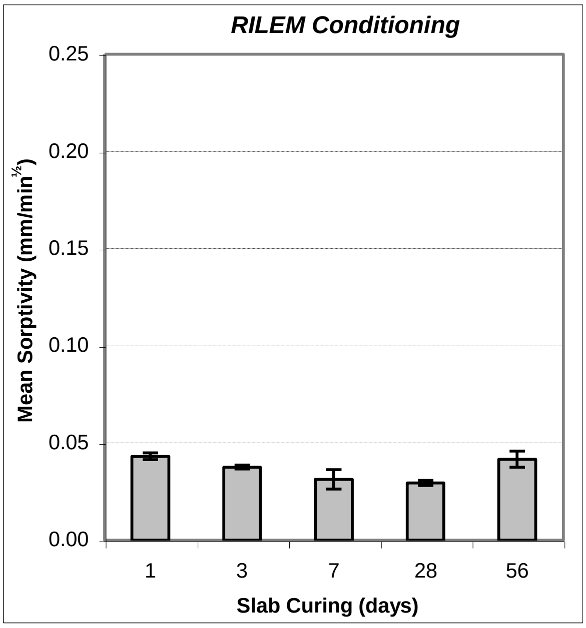

***Figure Six:*** *Mean sorptivity results for slab specimens conditioned by the RILEM procedure.*

The alternative conditioning regimes are less sensitive to the effects of curing. Drying at 105ºC appears to have minimised the improvement in concrete transport parameters expected between 3, 7 and 28 days curing. In the case of NIST and RILEM conditioning, the suppressed Sorptivity Coefficients resulting from the relatively wet test specimens, limit the precision with which differences in concrete quality can be distinguished. ***Figure Seven*** illustrates the difficulty: By 60 minutes into a sorptivity experiment, the mean rate of water ingress in a NIST or RILEM conditioned core can be as low as 0.012 grams/minute. Thus the cumulative water absorption over a 10 or 20 minute reading interval is comparable with the ± 0.1 g uncertainty typical in a laboratory balance of sufficient capacity to be used for a sorptivity test.

A consequence of the square root of time dependence in equation *(1)* is that improving the sensitivity of the test requires more frequent early measurements. This has practical limitations for the convenient testing of multiple sample replicates.

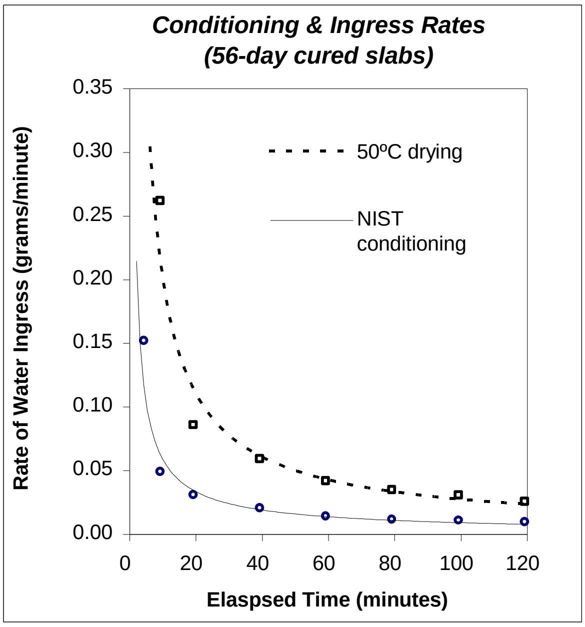

***Figure Seven:*** *Mean water ingress rates for two different conditioning methods.*

A comparison of sorptivity and compressive strength (***Figure Eight***) as a discriminator of curing is interesting. While the sorptivity testing indicates the benefit of extended curing, even up to 56 days, the compressive strength of the slab cured for 56 days is not significantly greater than the 7-day slab. This is a clear demonstration that the achieved compressive strength is not an adequate measure of durability because the bulk concrete, unlike the near-surface layer that controls durability, is generally somewhat insulated from poor curing practice.

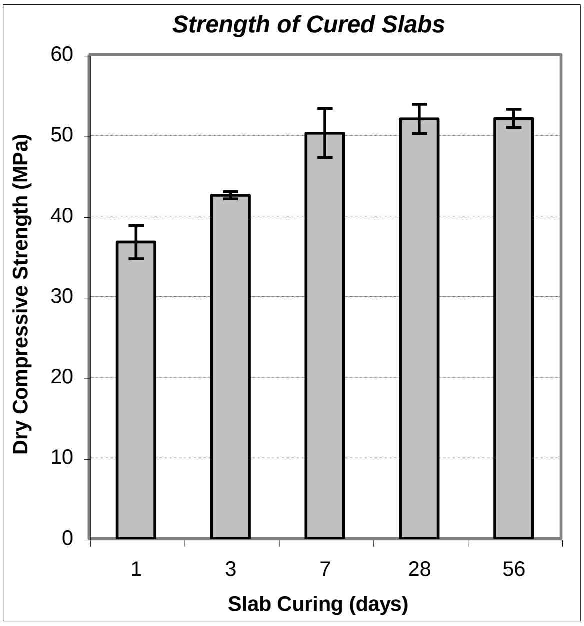

***Figure Eight:*** *Actual compressive strength of slabs 68 days after casting*.

An unexpected result was the large difference between the Sorptivity Coefficients determined on the slab cores and those obtained on cylinders. A large number of previous tests on cylinders from multiple batches of concrete to the same mix design had established a typical coefficient of 0.11 ± 0.01 (one standard deviation), when cured for 56 days and conditioned at 50ºC. The cylinders cast to accompany the current slabs gave a mean coefficient within this range (0.118 mm/min$^{½}$). However, the 56-day figure for the slab concrete, under the same conditioning regime, was reduced to 0.07 mm/min$^{½}$ (***Figure Three***). In terms of mix composition, this improvement appears to be approximately equivalent to moving from a 30 MPa concrete grade (290 kg/m$^3$, 0.6 w/c ratio) to a 50 MPa grade (420 kg/m$^3$, 0.42 w/c ratio), as ***Figure Nine*** demonstrates.

The precise reason for this dramatic difference between the sample types is unknown at present, although the density of the core specimens, at 2,450 kg/m$^3$, is approximately 40 kg/m$^3$ denser than the cylinder average, indicating at least some difference in compaction or aggregate distribution.

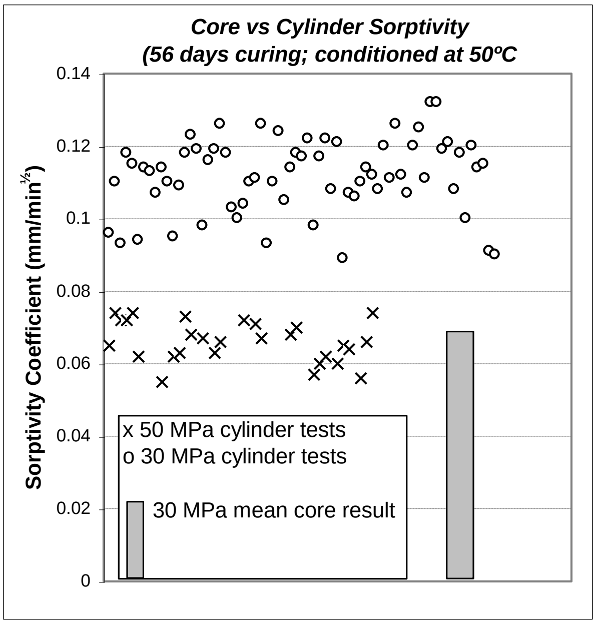

***Figure Nine:*** *Effect of sample type (core vs cylinder) on measured Sorptivity Coefficient.*

## CONCLUSIONS

Sorptivity is a durability parameter with the virtue of both simplicity of testing and sensitivity to concrete quality. However the influence of moisture content on concrete transport properties is so profound that it is mandatory to know the conditioning history of a test sample before any sense can be made of its Sorptivity Coefficient.

From the point of view of both ease of testing and sensitivity of results, drying at 50ºC appears to be the most satisfactory conditioning regime. The artificially elevated Sorptivity Coefficients obtained by this technique offer no real disadvantage to the use of the test as a simple durability index for characterisation purposes, or as a quality control technique. The need for transport coefficient measurements based on realistic moisture contents (e.g. for service life modelling) is currently limited. It should be possible to develop empirical equations that scale sorptivity as a function of internal moisture if a demand for these figures develops.

The apparent discrepancy between the sorptivity values obtained on cores and cylinders requires further investigation. It indicates that sorptivity is strongly influenced by factors such as compaction and aggregate distribution, in addition to mix composition and curing. This may make it difficult to use figures derived from laboratory trials as a basis for writing construction specifications that call up absolute sorptivity figures to be achieved in the field. A better approach may be a relative sorptivity specification, for example requiring that a curing regime is implemented sufficient that the sorptivity of the outer concrete skin is no larger than a fixed percentage of the interior concrete.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] Hall C, 1977, *Water movement in porous building materials – I. Unsaturated fluid flow and its applications*, Building Environment, **12**, 117-125.

[2] Martys N S, 1995, *Survey of transport properties and their measurements*, NISTIR 5592, US Department of Commerce.

[3] ASTM Subcommititee C09.66, 2001, *ASTM draft test method for measurement of rate of absorption of water by hydraulic-cement mortars or concretes.*

[4] Hall C, 1989, *Water sorptivity of mortars and concretes: a review*, Magazine of Concrete Research, **41** no 147, 51 – 61.

[5] Martys N and Ferraris C, 1997, Capillary transport in mortars and concrete, Cement and Concrete Research **27** no 5, 747-760.

[6] Ho D W S and Lewis R K, 1987, *The water sorptivity of concretes: The Influence of constituents under continuous curing*, Durability of Building Materials, **4**, 241-252.

[7] Standards Australia, 1999, *AS1012.21, Determination of water absorption and apparent volume of permeable voids in hardened concrete*.

[8] Quénard D and Sallée J, 1988, *The transport of condensable water vapour through microporous building materials*, IDS '88 International Drying Symposium, Versailles, September 1988.

[9] Alexander M A and Ballim Y, 1993, *Experiences with durability testing of concrete: A suggested framework incorporating index parameters and results from accelerated concrete durability tests*, Proceedings of the Third Canadian Symposium on Cement and Concrete, 248-263.

[10] Bentz D P, Garboczi E J and Lagergren E S, 1998, *Multi-scale microstructural modelling of concrete diffusivity: Identification of significant variables*, Cement, Concrete and Aggregates, **20** no 1, 129-138.

[11] Bentz D P, Ehlen M A, Ferraris C and Garboczi E J, 2001, *Sorptivity-based service life predictions for concrete pavements*, 7th International Conference on Concrete Pavements, Orlando, Florida, 181-193.

[12] Recommendations of TC 116-PCD, 1999, *Preconditioning of concrete test specimens for the measurement of gas permeability and capillary absorption of water*, Materials and Structures, **32**, 174-176.

[13] DeSouza S J, Hooton R D and Bickley J A, 1997, *Evaluation of laboratory drying procedures relevant to filed conditions for concrete sorptivity measurements*, Cement, Concrete and Aggregates, **19** no 2, 59-63.