89

Technical Note

TEST METHODS FOR THE ASSESSMENT OF DURABILITY OF CONCRETE

INTRODUCTION

This technical note discusses a number of test methods that may be used to assess the durability of concrete. Durability is a determining factor in achieving the design life of concrete structures, and significant advances have been made in techniques, equipment and test methods used to assess durability performance. These include simple absorption tests as well as more specialised pressure permeability and diffusivity test methods, with emphasis for both in-situ measurements and a combination of laboratory and sample extraction testing. There is now a greater trend to incorporate durability test methods into performance specifications, to ensure control and compliance during construction.

Many of the potential durability or permeability (penetrability) test methods can only be undertaken by experts in specialised laboratories. This lack of easy understanding precludes these tests from being used as routine compliance durability tests. Furthermore, due to the complexity of the apparatus involved, certain modifications to test procedures, such as input pressure, duration of test, moisture conditioning of samples etc, can be manipulated to achieve particular results and coefficients.

TRANSPORT MECHANISMS IN CONCRETE

Deterioration mechanisms which adversely affect the long term durability of reinforced and prestressed concrete bridge and other structures are generally associated with the ingress of various liquid or gaseous aggressive agents. It is widely accepted that all deterioration mechanisms affecting concrete are either influenced or promoted by the availability and transport of water through the permeable voids (interconnected voids) of the pore structure of concrete. Water provides the medium by which many aggressive agents (i.e. chlorides, sulphates etc.) are transported into concrete. It also affects the initiation and rate of some deterioration processes such as carbonation. Deterioration processes such as corrosion of the steel reinforcement, chloride ingress, alkali aggregate reactions, sulphate and chemical attack can be controlled by restricting the movement of moisture in the concrete, i.e. by controlling penetrability. For many structures the primary transport mechanism is considered to be absorption of surface water due to capillary suction, particularly in their early life[1].

Current objectives are to achieve low penetrability by modifying and refining the pore structure of the concrete (i.e. in terms of fineness, inderictness of path, discontinuity etc.) and therefore minimise the volume of permeable voids (VPV) [1,2,3,4]. This is generally achieved by the use of SCMs (supplementary cementitious materials) and other pore modifying admixtures which are capable of improving the impermeability of concrete. Durability can then be classified on the basis of the amount of VPV in the concrete. It can be directly applicable to all concretes, provided the constituent ingredients of the concrete are controlled by specifications and good construction practices are the norm.

Most deterioration problems associated with bridges and other structures mainly occur in the atmospheric zones and are areas which are subject to a continuous wetting and drying process such as tidal and splash zone areas) or areas which are partially submerged. Under these conditions the concrete is not totally saturated and it is certainly not subjected to hydraulic pressures. As water permeability is not the predominant transport process, pressure permeability test methods cannot be considered as relevant to determine the quality or durability of such concretes. In relation to ionic diffusion, considering that this is more significant when the concrete is saturated, it follows that initial control of capillary absorption would limit both the initial bulk transportation of the aggressive ions into concrete and the subsequent slower diffusion. Chloride diffusion will be minimised due to less water-filled pathways through which diffusion can occur, lower surface chloride levels and of course reduced concentration gradients.

Thus capillary absorption appears to be the predominant transport mechanism which may directly influence the durability of concrete structures in many environments. Absorption can be influenced by changes in the mix design and other design and construction measures to make concrete more impermeable and more durable. By calculation of the water absorption and the directly related VPV value of concrete in accordance with test method AS 1012.21[3] (originally ASTM C642)[4] would give a good indication of how well a concrete structure could resist the various water borne agents and hence an indication of the concrete's durability.

DURABILITY TEST METHODS

Volume of Permeable Voids (VPV, AS 1012.21)

The selection of the VPV test method as the durability control test for the VicRoads specification Section 6105 was greatly influenced by the need to identify a simple rapid test procedure, which was also an existing national standard and which best reflected the transport mechanism associated with concrete for bridges and similar structures. Capital investment in the simple equipment required for this method is very minimal and can easily be undertaken by any NATA registered laboratory. A large number of specimens can be tested simultaneously and a full AS 1012.21 test would take approximately 10 days to complete. The test method has a very practical application and is well suited as a tool for quality control and durability assessment, particularly as specifiers and designers alike are looking for some test that is quick, simple and readily understandable. Very importantly the method is sensitive to even small changes in such durability influencing factors as, water/cementitious material ratio, mixture constituents, concrete grade, curing environment and construction practices, as well as, the degree of hydration and the refinement of the pore structure (i.e. permeable voids).

The VPV test method gives a measure of the interconnected void space within the concrete (i.e. capillary pores, gel pores, air voids and micro cracks), that can absorb water following normal immersion and subsequent boiling as a result of capillary suction. This is related to the ease with which water and water-borne ions enter the concrete and initiate corrosion. As the amount of water that can be absorbed into concrete is a function of the permeable pores of the concrete, it is considered that concrete with fewer permeable pores or voids should better withstand an aggressive environment than concrete with more permeable pores or voids. Durability, which is the ability of the concrete to withstand an aggressive environment, can then be classified on the basis of the amount of VPV in the concrete. The VPV method has a history of being used routinely for the prequalification of concrete mixes and the associated curing regimes, and as a quality control tool to ensure compliance in cast in place work, including sprayed concrete and the manufacture of precast concrete products. The method is also used as a diagnostic tool as part of condition surveys of existing concrete structures. Several steps in the test process are illustrated in Figures1 and 2.

The VPV is the only test method which has a proven repeatability (i.e. ±3%, VPV value of 0.3) and reproducibility (i.e. results between different laboratories is within ±4%, VPV value of 0.4)[6] record. This compares favourably with the reproducibility of compressive strength, which is of the order of ± 10%. Other test methods do not have any proven record in relation to repeatability and reproducibility. The VPV has the ability to monitor the variability of various ingredients in concrete mixes and allow improvements to be made with particular emphasis on the control of the total water in the actual concrete mix.

The VPV classification limits and their effectiveness (refer Table 1) were developed based on the assessment of extensive data generated over the past 15 years at least, by calibrating these limits to the optimum performance of laboratory concrete mixes, as influenced by W/C ratio; cementitious material type and content, concrete grade and strength; curing regimes; type and adequacy of compaction (i.e. vibration, rodding); testing of concrete cores extracted from in-situ structures and precast components and correlating with cylinders procured from site, as well as comparing with the condition of previously diagnostically investigated concrete structures; and comparisons with other research work.

Chloride Diffusion (i.e. Nordtest NT Build 443[7])

This test method is underpinned by theoretical assumptions from Fick's Law of diffusion. It is considered that the method determines a very conservative diffusion coefficient (D) parameter which in effect would force the design and manufacture of a more conservative concrete (more difficult to replicate in practice either at the batching plant or on-site due to the inherent inadequacy of quality control) than would otherwise be required if more realistic parameters were used. The diffusion behaviour of chloride ions in concrete is a more complex and complicated transport process than what can be described by the Fick's Law of diffusion. The different drift velocities and movement of the various ions and chloride ions in solution, the chemical binding, along with other factors, interfere with the transport of chloride ions. The effect of this ionic interaction significantly reduces the chemical potential and thus the driving force of the diffusing species. However, the application of Fick's Law assumes diffusion only from one side and straight forward without any other interactions and it therefore determines a much lower chloride diffusion coefficient (D) than what it would otherwise be the case. As such the model is not strictly correct as it does not give consideration to factors such as the effects of carbonation, chloride binding, ongoing cement hydration and curing particularly at increasing depth and of course the movement of chloride ions through capillary absorption.

Most deterioration problems associated with bridges and other marine structures mainly occur in the atmospheric zones and areas which are subject to a continuous wetting and drying process such as tidal/splash zone areas or areas which are partially submerged. In such environments the primary transport mechanism is considered to be absorption of surface water due to capillary suction, particularly in the early life of the structure. In environments where concrete drying is possible, water absorption may lead to very rapid penetration of aggressive agents dissolved in water. Ion diffusion (i.e. chlorides etc) is a very slow process and is only significant where the concrete is nearly or completely water saturated. In real marine bridges the in-situ tidal/splash and atmospheric zones are never completely saturated. This is in contrast to the chloride diffusion test method such as Nordtest NT Build 443[7] which requires that 28 day old concrete test samples which are totally saturated are immersed in a chloride (simulated seawater) solution for at least 35 days. Considering that chloride ion diffusion is more significant when the concrete is saturated, it follows that initial control of capillary absorption would limit both the bulk transportation of the aggressive chloride ions into concrete and the subsequent slower diffusion.

The determination of the chloride diffusion coefficient (D) for in-situ structures can not be based on very limited historical data (i.e. from two or three locations). Limited data can result in an inaccurate and unreliable curve of best fit from which D is derived. A more developed profile of chlorides (i.e. at least five locations) is necessary to make a more appropriate measurement of D. In addition, the value of D can be very sensitive to the surface chloride concentration (C_s) assumed in the first place and as such a higher assumed C_s would result in a lower D value.

Water Permeability (i.e. DIN)

This is the most widely researched method with a number of variations available. However, it is mostly applicable for testing of submerged structures which are under hydrostatic pressure, rather than structures in atmospheric zones or partially saturated. There are many problems inherent in permeability measurements. These include continuing hydration, especially when testing concrete which is not fully cured and also solids (e.g. $Ca(OH)_2$) dissolving from one location and firmly precipitating in another location. These have the effect of blocking interconnected pores and therefore reducing permeability. This test requires at least one to several weeks to complete.

Rapid Chloride Permeability Test (ASTM C12028)

The rapid chloride permeability test (RCPT, ASTM C1202[8]) involves the application of a potential of 60V DC across a 100mm diameter x 50mm thick slice of concrete conditioned by vacuum saturation. One end of the samples is immersed in Sodium Chloride and the other in Sodium Hydroxide. The full test would take about three days to complete, with 6 hours required for the actual test. The total electric charge passed (coulombs) is a measure of the chloride ions migrating through the concrete under the described conditions. However, this method has been criticised as not really measuring permeability (movement of chloride ions) but resistivity of the water saturated sample.

The RCPT may also suffer from possible interferences (as indicated in ASTM C1202) and these should be considered in the interpretation of results. Interferences affect the resistivity (conductivity) of the concrete and this in turn affects the coulomb value obtained. Interferences may include the degree of moisture in the specimens, presence of reinforcing steel or ions other than chlorides, use of SCMs and other admixtures etc. Furthermore, it has the potential to overheat test samples, particularly with younger concrete, which would result in damage and therefore distortion of the test data.

Sorptivity Test (i.e. CSIRO)

It is considered that the sorptivity test method is unable to be used as an effective quality control tool due to the length of period of the test. The turnaround of results would be something of the order of 8 to 10 weeks. As such it has the inability to really influence the ongoing quality of concrete during manufacture and construction and thus it is unable to provide some continuous relationship to quality control and the original design of the concrete mix. However, the greatest concern with this method is related to the non-uniform conditioning of samples. After demoulding following the required curing, specimens are dry conditioned in a room or chamber (23 ^oC and 50 ± 5%) for a minimum period ranging from 21 to 35 days depending on the exposure conditions. This type of conditioning is considered unsatisfactory because it can not assure the uniform and constant conditioning of all samples (i.e. constant mass preconditioning for all samples). Considering that the moisture content of the test specimens strongly influences their sorptivity values, the test tends to discriminate in favour of higher strength concretes as they would dry more slowly. The increased rate of moisture loss in lower strength or poorly cured concretes would tend to cause greater micro cracking which would increase the measured sorptivity. Higher strength concrete specimens on the other hand would tend to produce less micro cracking at the start of testing due to the reduced rate of moisture loss.

Initial Surface Absorption Test (ISAT, BS1881)

This test is designated by the British Standards in BS18819 and can be used on laboratory or field concrete. The test measures the rate at which water is absorbed into the surface of the concrete. It does not measure the bulk permeability (penetrability) of concrete. Field samples can only be tested if no water has fallen onto the test surface in the previous 48 hours. This test has been chosen by a number of designers for compliance testing in the Persian Gulf. The test has a record of being used in the UK for the purpose of assessing durability for concrete paving flags and kerbs.

Porosity Tests (i.e. RILEM)

Such tests include helium and mercury porossimetry and some RILEM tests. The small and inert helium molecules are used to penetrate cementitious systems which have restricted pore openings. This method is based on Boyle's Law for isothermic gas expansion. Higher pressures and oven drying of specimens are required. The mercury intrusion process (MIP) involves the injection of mercury into the concrete under pressure and the measurement of the mercury ingress. Some variation in results has occurred during testing.

Gas Permeability (i.e. RILEM)

This utilises gases such as nitrogen and requires elaborate apparatus and conditioning of specimens, although it is a much quicker test. Problems are encountered in this test as moisture in the capillaries acts as a barrier to the gas. In addition, most contaminants are introduced into the concrete as water borne substances, and most deterioration reactions can only take place in substantially moist environments.

COMMENTS ON DURABLE CONSTRUCTION

In general it is considered that a relatively dense and impermeable concrete cover based on high performance SCM concrete in conjunction with a multi-level protection approach consisting of various durability provisions, and good quality control for both concrete supply and construction, is what is required to deliver a long lasting structure to satisfy the specification requirements. This approach includes the use of the VPV test method as a tool for prequalification of concrete mixes and as a quality control tool during construction and from in-situ cores. Such a durability strategy has been used effectively at the Patterson River Bridge in Melbourne[6]. Monitoring has continued over the past 12 years using at least six macro cells with galvanic current corrosion monitoring probes, and a dummy probe placed in a porous concrete slab situated on site.

SUMMARY

The link between the VPV test method (and indeed all other durability test methods) and the design life of concrete structures is still being developed and will be further enhanced and refined as more comparative data is generated. However, the VPV durability classification limits as stated in Section 610[5] were developed based on the assessment of extensive data generated over a significant period of time [1,5]. At this stage it is considered that the best approach to achieving durable concrete structures in marine and other environments (i.e. 100 year service life) is a total package of durability related measures including strength development, low W/C ratio, low VPV, low shrinkage values and soluble salts, limitations on alkali/aggregate reactivity (AAR), good curing practices and compaction and of course great attention at all times to the vital interaction between the technical and on-site practical requirements. It is considered that VPV testing will act as a deterrent to excessive additions of water in concrete, as well as, other bad practices adopted at the construction site which can influence its long term performance and durability in a more superior manner than any other durability test method.

TABLE 1 VPV Limits for various concrete grades[5]

Concrete Grade	Maximum VPV Values at 28 days(%)[1]		
	Test Cylinders (compacted by vibration)	Test Cylinders (compacted by rodding)	Test Cores
VR330/32	14	15	17
VR400/40	13	14	16
VR450/50	12	13	15
VR470/55	11	12	14

Note 1:For the purpose of satisfying the requirements of Section 610[5], test results with a VPV value of equal to or less than 0.5% higher than the maximum allowable for the corresponding concrete grade, may be rounded down to the nearest whole number.

REFERENCES

1. Andrews-Phaedonos, F. (1996) "Establishing the Durability Performance of Structural Concrete", VicRoads, Melbourne, Australia, January.
2. Andrews-Phaedonos, F. (1997) "Recommended Durability Classifications for Structural Concrete Based on the Measurement of Volume of Permeable Voids (VPV)", CANMET, Durability of Concrete Conference, Sydney.
3. Australian Standards, AS 1012.21, "Determination of Water Absorption and apparent volume of permeable voids in hardened concrete."
4. ASTM C642 "Test method for specific gravity, absorption and voids in hardened concrete".
5. VicRoads Standard Specification (2005), Section 610 "Structural Concrete".
6. Andrews-Phaedonos, F. (1997), "Durable concrete construction – Patterson River Bridge, Nepean Highway, Melbourne, Victoria". AustRoads Bridge Conference 1997, Volume 1, pp. 353-364.
7. Nordtest Method NT Build 443, "Accelerated Chloride Penetration in Hardened Concrete".
8. ASTM C1202, "Test method for electrical indication of concrete's ability to resist chloride in mortar and chloride ion penetration".
9. British Standards, BS1881, "Surface Absorption Test (ISAT)".
10. Andrews-Phaedonos, F. (1992), "Condition Survey of South Gippsland Highway Bridges", Rehabilitation of Concrete Structures, Proceedings of the International RILEM/CSIRO/ACRA Conference, Melbourne.

CONTACT

For further information on durablity of concrete, please contact:

Fred Andrews-Phaedonos Phone (03) 9881 8939
or on Mobile 0419 597 277
Email fred.andrews-phaedonos@roads.vic.au
GeoPave Facsimile (03) 9881 8900

Figure 1 – Standard test cylinder cut into four slices. Following oven drying, specimens are allowed to cool in a desiccator

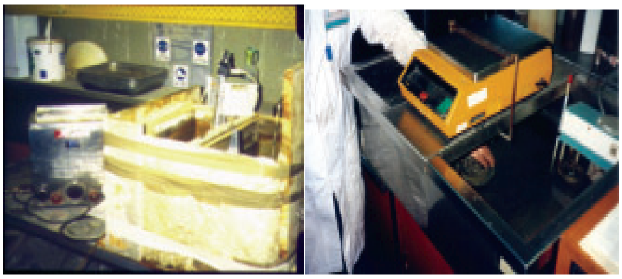

Figure 2 – Specimens are immersed in water at standard temperature followed by boiling as part of the process. Specimens are then weighed under water