RELIABLE, SIMPLE AND CHEAP PERFORMANCE FIELD TESTS FOR PREDICTING LONG TERM DURABILITY OF CONCRETE STRUCTURES

by Ir. Dr. Kribanandan GURUSAMY NAIDU.
BSc, Phd, CEng, MICE, PEng, MIEM
MANAGING DIRECTOR
JTK CONSULT SDN BHD, MALAYSIA
www.jtkconsult.com.my

ABSTRACT

Despite the explosion of knowledge and understanding of the problems of concrete durability, premature deterioration continues to plague the construction industry particularly where Marine environments predominate. In this connection, the development of field durability performance testing which is reliable, simple to use and cost-effective has been the focus of many a researcher and test company alike. The paper will review existing tests which are commercially available and consider these in turn for adoption as part of a delivery of good quality concrete which can achieve targeted long term life cycle performance.

INTRODUCTION

Information from research into concrete durability has increased the fundamental understanding of concrete as a material and the complex interactions between material, environment and structure which cause deterioration. Although durability specifications have become progressively more stringent in response to a perceived lack of durability of reinforced concrete, modern structures have not always shown a corresponding improvement in durability. This appears to be due to a lack of understanding of what is required to ensure durability and inadequate means of enforcing/guaranteeing compliance with specifications during construction.

Chloride-induced corrosion of reinforcement is manifested in two primary forms: cracking and spalling of the cover concrete due to the expansive nature of corrosion products generated at the reinforcement; and local pitting at the anode which reduces the cross-sectional area of the steel. Many marine structures in Malaysia and South East Asia exhibit severe corrosion damage.

While part of the problem may be attributed to the design and construction process (e.g. poor detailing, low cover, inadequate curing), it is also recognized that design of reinforced concrete to current British Standard (BS) Codes for instance, does not necessarily lead to long life structures in some of the most severe exposure conditions [(1)]. A more structured, engineering approach to durability design is needed, therefore, and this has been recognized for many years [(2)].

The achievement of durability in a concrete structure depends upon :

a) the appropriate selection of exposure class
b) suitable design and detailing

c) an appropriate specification for both the concrete and the execution of concreting works
d) the supply of fresh concrete to the specification
e) good site workmanship, particularly with respect to achieving the specified cover

Failure to reach expectations at any of these stages may result in lower than intended durability. In this context the need to develop field performance testing which are reliable, simple to use and cost effective has never been more critical and is a prerequisite for the achievement of durability and lowest life cycle costs.

THE DURABILITY PROBLEM

In freshly cast concrete the steel is protected by the highly alkaline environment (pH 13). The large amount of calcium hydroxide buffers the pH in the pore solution to about 12.5 and the small amounts of sodium and potassium present in the cement push this to a higher value. In these conditions a protective oxide layer is formed and maintained on the surface of the steel.

Loss of protection can occur as a result of either carbonation of the concrete or due to the ingress of chlorides (commonly from sea water or de-icing salts). In each case it is clear that it is the quality of the cover (the covercrete [(3)]) to the reinforcement which determines the time to corrosion activation (Figure 1).

Chloride ingress inhibits the mechanism of maintenance of the protective oxide layer which, in uncontaminated concrete, is undergoing a continuing process of breakdown and immediate replenishment.

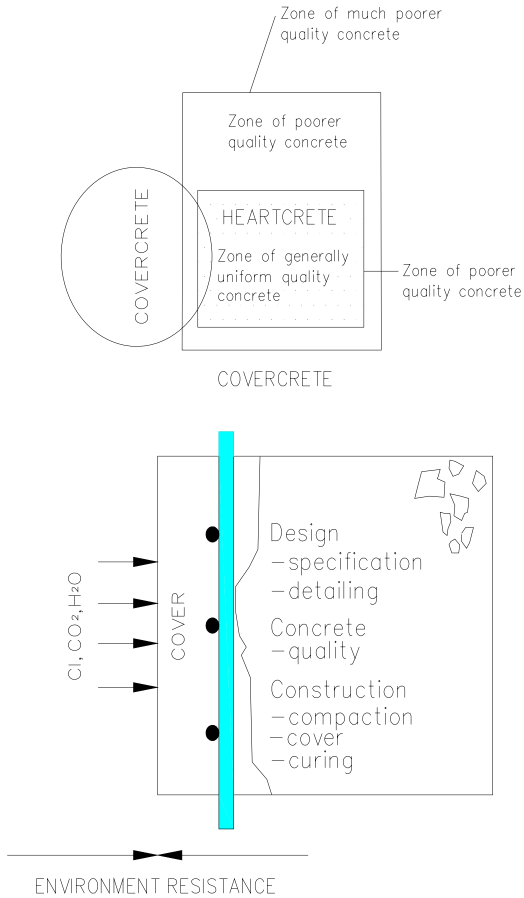

Figure 1. Normal variations in concrete quality through a section of a beam and factors influencing the quality of the near surface zone (after Dewar [3])

In relation to the prevention of reinforcement corrosion it is clear, therefore, that it is the near surface zone, or **covercrete** [3] which determines the durability. Moreover, even when exercising normal good practice, this zone tends to exhibit poorer qualities, e.g. higher absorption [4], than the bulk of the section, or **heartcrete**. This is illustrated in Figure 1.

The variations in quality arise from water gain (at the top surface in particular but also against normally formed surfaces) and difficulties in compacting concrete in the cover between the reinforcement and the form face. To enhance durability it is often necessary, therefore, to improve the resistance of the near surface zone to the ingress of chlorides, carbonation and moisture.

APPROACH TO DESIGN FOR DURABILITY

It is often claimed that "all that is needed to achieve a long service life is good quality concrete and adequate cover to reinforcement" and this deemed to safety approach is the basis for durability design in current codes and standards, despite the complexity of the process involved. For the *most severe* conditions, with no abrasion, BS 8110 for instance[5] requires 50mm cover when using grade 50 concrete with a maximum w/c of 0.45. Using the same grade 50 concrete under the same exposure conditions, this is reduced to 40mm in BS 5400 [6] for bridges; with 50mm cover a grade 40 concrete is permitted. For maritime structures, BS 6349 [7] requires 50mm cover (with 75mm preferred).

Based on measurements of chloride ingress within structures it can be demonstrated that levels of chloride required to cause activation can be achieved at rebar depth in relatively short periods. For example, with w/c = 0.45 and 50mm cover, the chloride level may exceed 0.4% wt of cement (the commonly assumed corrosion threshold level [8] within 20 years [9]. If on the other hand, as a result of poor design detailing, the concrete cannot be properly compacted around congested reinforcement, or if the specified cover is not achieved, or if concrete is not properly cured, then corrosion activation may commence even earlier. Many of the problems seen today, for example, bridges which exhibit deterioration in less than 20 years [10], have been the result of poor workmanship or low cover. However, it was also reported that "few cases of corrosion have been reported where cover exceeds 50mm". Thus, even with good quality concrete and adequate cover there may be a significant risk of corrosion within the life of many structures. This is acknowledged in many of the codes which state that, in very severe exposure conditions, additional protective measures may be needed. Limited guidance is given on what measures are appropriate but the codes provide no information on the full range of options available or on their influence on design life. In relation to chloride induced corrosion in particular, there is a need to supplement existing code requirements if the number of premature failures is to be reduced.

Designing for durability by appropriate performance specification is certainly the way forward to achieving adequate long term performance. However to ensure this is achieved it is imperative that quality control systems and the associated testing are developed to demonstrate compliance during construction. The latter is the missing weak link which needs to be addressed by the industry. Traditionally concrete has been specified by characteristic strength and these requirements are fairly well developed. Concrete strength itself does not define durability. Several factors in combination need to be considered and these are discussed below.

FACTORS AFFECTING CONCRETE DURABILITY IN THE MARINE ENVIRONMENT

Deterioration of marine concrete is generally associated with external agents such as chlorides which penetrate into the concrete causing damage. Using the premise that the potential durability of reinforced concrete is determined by the protection provided by the cover concrete, a number of factors affecting marine concrete durability may be defined. These include concrete type, cover depth to reinforcement, site practice and the severity of exposure.

Concrete Type

The type of concrete used to protect the reinforcement has a major influence on durability since the material controls the rate at which aggressive agents move through the cover concrete. Current codes of practice make allowance for the improved chloride resistance of higher grade concretes but largely ignore the influence of binder type. Chloride ingress into concrete is not only determined by the permeability of the pore system but also by interactions between the material and the diffusant which depletes the concentration and, with time constricts the pore structure. Concretes containing fly ash and slag have been shown to have exceptional chloride binding characteristics and produce concretes of high chloride resistance [(11)].

Cover to Reinforcement

The potential durability of reinforced concrete is greatly enhanced if adequate cover to reinforcement is specified and monitored for compliance on site. For sufficient protection to reinforcement under marine conditions, cover should be in the region of 50 to 75mm. Reduced cover is risky even when using high quality concrete since defects such as cracks and voids become more significant than they are with normal cover and may provide a low resistance path to the reinforcement. Increasing cover may result in increased crack widths at the surface. Cover greater than 75mm should be used with caution due to the potential for cracking at the concrete surface and may also be impracticable for many structures.

Site Practice

Poor site practice, particularly with regard to placing, compaction and curing of concrete may negate the benefits of good design and materials selection. Research has established the value of good site practice such as active moist curing in improving the near surface properties of concrete [(12)]. Specifications have been proposed to control these site activities, but unfortunately adequate supervision and suitable methods to monitor compliance have not been implemented on site. The inability to ensure consistent quality of concrete on site is considered to be a major reason for the continued prevalence of concrete durability problems.

Severity of Exposure

The severity of marine exposure varies considerable depending on factors such as climate, location relative to the sea and structural considerations. Current codes of practice provide limited guidance about exposure conditions and generally define only two categories : extreme exposure for concrete subjected directly to the full abrasive action of the sea, and very severe exposure for concrete subjected to sea water spray or mild abrasive/wave action. The wide variations of exposure in the marine spray zone are not adequately defined by these categories. This is particularly problematic since most marine concrete structures are located in the splash zone. Given the range of marine conditions, a more comprehensive and rationally structured system for defining the severity of exposure needs to be formulated.

COMPLIANCE TESTING OF SITE CONCRETE

Good designs and materials may be compromised by poor construction practice, and controls need to be established and implemented to ensure satisfactory execution of designs on site. Durability audits should be carried out after construction of structures exposed to harsh marine conditions in order that early preventive action can be taken. A variety of techniques have been developed which are able to assess the quality and potential durability of site concrete, but few have gained acceptance in construction contracts.

Ensuring adequate cover to reinforcement is likely to have the greatest impact for improvement of concrete durability. Cover depths cannot be ensured merely by checking cover before placing of concrete and it is essential that cover surveys are done after construction to locate any inadequate cover.

Durability performance tests such as the chloride conductivity test may also be used to assess the quality of site concrete and these techniques are likely to assume greater significance in monitoring construction in the future. Durability audits after construction using these techniques have become a reality but are a long way from becoming standard practice for structures exposed to extreme conditions.

Performance based specifications for durability have the advantage of making it possible to quantify the near surface resistance of concrete so that rational designs may be implemented and satisfactory quality of site concrete ensured. Durability tests such as sorptivity, the Initial Surface Absorption Test (ISAT), or the Figg test are sensitive to changes in concrete pore structure which affect durability and are recommended for use as durability performance specifications. The chloride conductivity test should ideally be used at the design phase of a marine structure to optimize concrete materials. Sorptivity testing and/or ISAT may be used to measure curing effectiveness during construction, while the Figg air permeability testing, being sensitive to major defects caused by poor construction such as inadequate compaction, segregation or cracking, should provide useful information about the quality of the cover concrete. Durability testing should ideally be done at early ages (28 days or some other defined age) and could coincide with the well established procedures for concrete strength testing which is universally practiced in all construction projects.

STAGES IN QUALITY

To develop a long term life cycle perspective of a structure there needs to be a means to enforce/guarantee compliance with specifications during construction and during usage. Two broad perspectives need to be considered including :

Task 1 Quality Control/Quality Assurance before, during and after placement of concrete and

Task 2 The condition analysis of existing structures during usage. This is not dealt with in this paper

Figure 2 provides the quality assurance/quality control flowchart for a new project. It is clear from Figure 2 that the QA/QC requirements can be broken down into four distinct parts. Each incorporating a group of related requirements.

QUALITY ASSURANCE/QUALITY CONTROL OF NEW CONCRETE

Introduction

In general, the influence of constituent materials and mix proportions on the properties of fresh, early age and mature

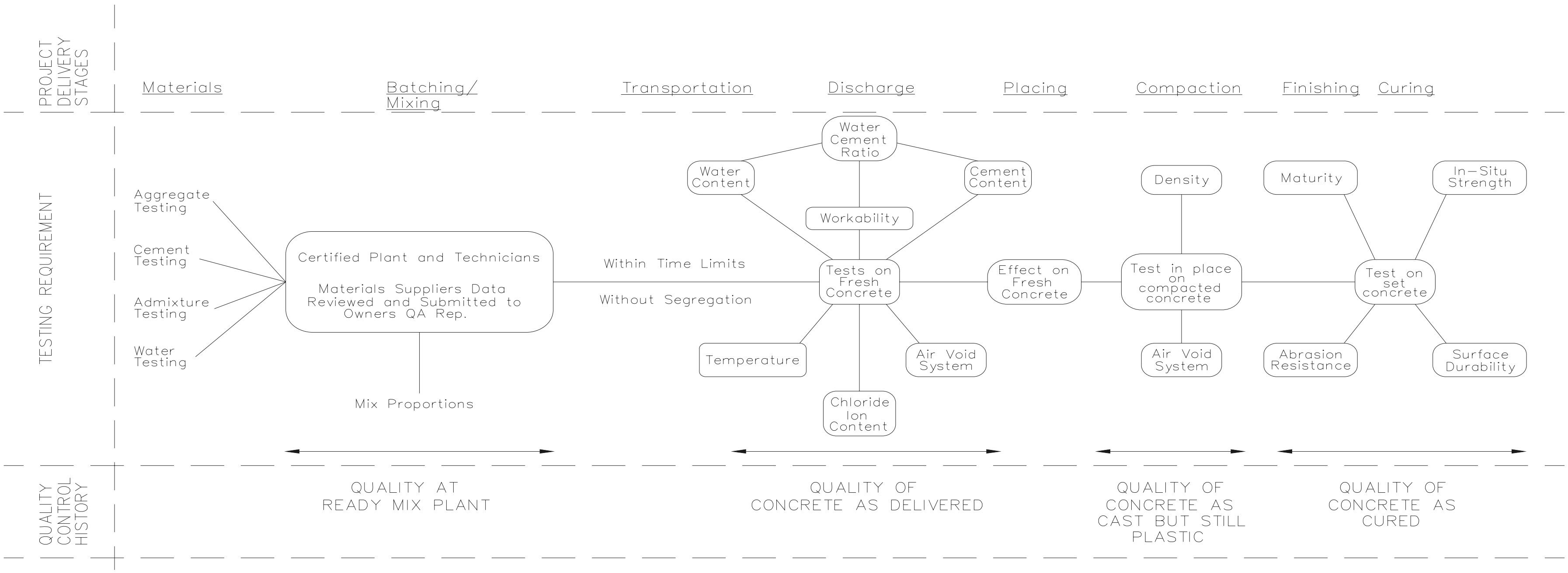

FIGURE 2 : QUALITY CONTROL/QUALITY ASSURANCE FLOW CHART

concrete is well understood and mixes can be designed to achieve specified characteristics for a variety of exposure conditions. The constituent materials for concrete are variable, however, and quality control is required to enable changes to be detected and accommodated in the mix design and production process.

As there are many stages in the production of concrete it is inevitable that quality control must be exercised at each stage through materials handling, mixing, transportation, placing and curing. Furthermore, the requirements for testing at a particular stage may be dependent on testing at other stages. For example, if the cement content is adequately controlled and checked at the mixing plant subsequent checks for cement content may not be necessary and w/c ratio can be reliably determined, by measurement of water content only on site. For other properties, such as the air content and bubble size distribution, the production process may result in changes and the only reliable control check may be on the concrete after placing and compaction, regardless of what has been recorded previously.

In evaluating a particular test method, therefore, consideration has been given not only to the performance of the test itself, but also to how the test fits into the *QA/QC* system, and with the information already obtained.

QUALITY OF CONCRETE AS DELIVERED

For the quality assessment of the concrete on arrival at the construction site, the key characteristics which will have been specific are workability, water/cement ratio, minimum cement content, air void parameters, concrete temperature and free chloride content. To minimize disruption to construction schedules it is essential that the test for the above concrete characteristics can be performed immediately and rapidly.

It is universally accepted that water/cement (w/c) ratio is of paramount importance in controlling the properties of the concrete and limitations on w/c ratio are frequently specified in order to control strength or durability. Unfortunately there is as yet no easy direct method of measuring w/c ratio on site. Reliance is usually placed on batching plant records or measurement 'of compressive strength which is assumed to reflect underlying changes in w/c ratio :

With the growing realization of the importance of ensuring the durability of concrete, there is a clear need for a rapid method of accurately determining w/c ratio which can be used for routine quality control during concrete production.

QUALITY OF CONCRETE AS CAST BUT STILL PLASTIC

Testing during this phase needs to deal with the assessment of what effect the operations of placing and compacting have on the concrete's properties.

On typical construction sites, an area of inadequate compaction will normally only be discovered when it is too late to correct the flaw. Areas of honeycombed concrete are obvious when forms are removed and may be repaired by grouting or patching, although the finished product will never be comparable with correctly compacted material. If the flawed area is not immediately visible, the long term cost can be significant - structural inadequacy, high permeability and early deterioration are possible consequences.

The assessment of the degree of compaction while the concrete is still plastic, and while corrective measures can still be taken, is therefore a highly desirable capability for quality control, in terms of both cost and structural durability.

Several methods can be considered here including gamma-ray measurement techniques and possibly Impulse Radar or Impact Echo. This is an area which requires further research and development.

QUALITY OF CONCRETE AS CURED

In-situ Strength/Maturity

For over 80 years, the most widely used test for concrete has been the compression test of the standard cube or cylinder and today this is used, suitably modified by constants that relate design stresses to the compressive strength value, as the standard for structural design calculations.

The main drawback of this procedure is that the cube/cylinder test represents the potential strength of the concrete delivered to site, not the strength of the concrete in place. Thus standard cube/cylinder tests cannot be used with confidence for determining if adequate strength has been attained for safe removal of formwork, etc.

However, it has been shown that the use of a variety of in-place tests can satisfactorily determine in-situ concrete strengths thus increasing safety and decreasing construction costs by permitting accelerated construction schedules.

The non-destructive evaluation of early age strength has been of major interest to researchers over the last twenty years and dozens of techniques have been proposed. These include in order of preference Ultrasonic Pulse Velocity methods (UPV), surface hardness methods (Rebound Hammer), Pull out testing (Lok-Test, CAPO test) and penetration resistance testing (Windsor probe). These NDT methods are well developed and in common usage and will not be discussed further here.

Concrete Cover to Reinforcement

Failure to achieve the specified cover is probably the greatest single factor influencing the premature corrosion of reinforcement. In chloride environments problems may also be due to the specification of inadequate cover. As the protective capacity of a given concrete is broadly related to the square of the cover, performance can be highly sensitive to deficiency in cover and measures taken to control cover may secure more positive benefit than the pursuit of any other controlling parameter.

Figure 3 shows that much of the actual cover may be considerably below the nominal value specified by the designer. In aggressive environments this may result in a significant reduction in service life. It also shows that the variation in cover generally followed a Gaussian distribution and that the mean location of the reinforcement compared closely with the nominal cover [13].

Structural design is based on the nominal cover. Explicit durability design should be based on characteristic minimum cover which will depend upon the exposure conditions and the durability properties of the concrete selected.

If required cover is obtained from a UK code of practice, such as BS 8110[5], the value is usually expressed as a nominal value and can depend upon the grade of concrete. According to BS 8110, nominal cover is the dimension used in design and indicated on drawings and, amongst other requirements, should protect the steel against corrosion; the actual cover should never be less than the nominal cover minus 5 mm.

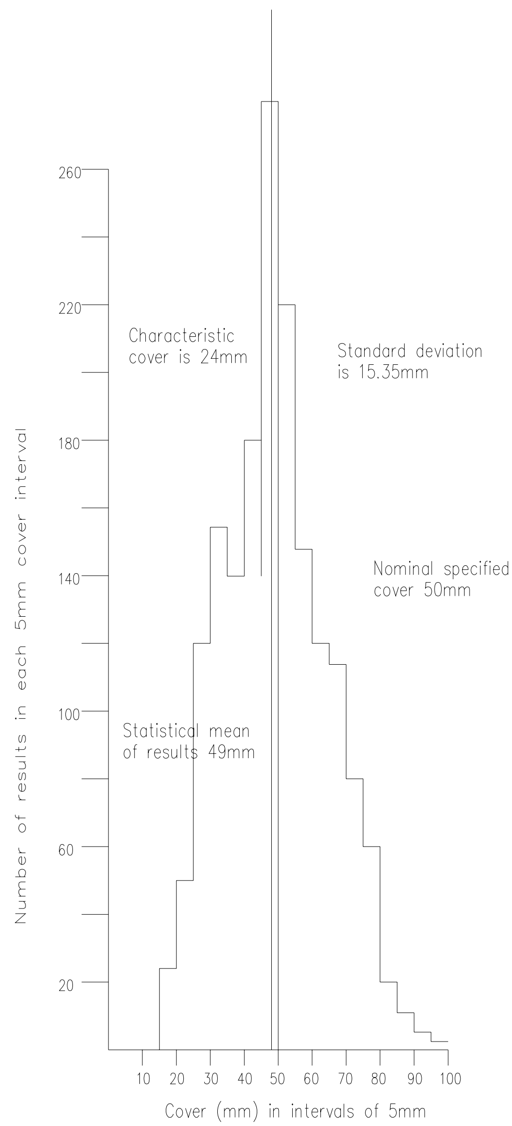

Figure 3 Distribution of cover – Analysis of 1600 cover meter readings for a 13m high retaining wall (after BN sharp as reported in reference 13)

As illustrated in Figure 3, the 5mm allowance in BS 8110 between the nominal cover and the characteristic minimum cover is inadequate and this has been confirmed by several researches. Based on a concrete society [13] survey of several recommended practices a 5 to 15mm allowance needs to be provided for in-situ concrete and for pre-cast work where the covers are confirmed by quality control, an allowance of between 0 to 5mm cover is adequate. Where it is not practicable to check the cover after placement of the concrete, for example over the faces of massive structures or for buried structures, the higher margin may be appropriate.

Performance testing of cover, in practice, is restricted to direct measurements on the structure prior to concrete placement and non-destructive measurement in the hardened concrete. Where performance specifications are used there will need to be a requirement to complete a cover meter survey on the finished structure. The extent of this can be varied depending on the severity of exposure condition and criticality of the component.

In using the cover meter a calibration is recommended and this can be done by casting a beam from the concrete being used on site containing an offset reinforcement bar from the site.

IN SITU MEASUREMENT OF SURFACE DURABILITY

The performance of the near surface (or cover) zone has been increasingly acknowledged as a major factor governing the rate of degradation of reinforced concrete structures, providing the first barrier to aggressive agents which either attack the concrete directly or cause initiation of corrosion of reinforcement. In both cases moisture plays an important role and a low sorptivity concrete would therefore imply high durability. The surface layer also determines resistance to mechanical damage such as abrasion for flooring applications.

It is clear that there exists a need to quantitatively determine the surface characteristics of in-situ concrete, either directly or indirectly at a relatively early age. Furthermore, the results obtained should provide information which can be used to predict likely deterioration rates for a particular exposure condition, and hence to assess compliance with the specified design life.

The most predominant mechanism associated with concrete is the ingress of water. The extent of reinforcement of corrosion, freeze thaw damage, sulphate attack and ASR all depend on the availability of moisture.

Hence any test method for durability should enable measurement of the migration of water into the concrete, relative to a standard initial moisture state, and ideally provide absolute material property data (eg. sorptivity) rather than an 'empirical permeability index'.

The test method should also be capable of reflecting the changing properties of the surface zone with depth. Some test methods involving drilled holes excluding a large proportion of the surface zone from the measurement by plugging the near surface layer. However, in virtually all deterioration mechanisms the surface skin provides the initial barrier to attack. The test method should, therefore, at the very least provide an assessment of the integrated quality of the cover zone.

A number of penetrability techniques which measure absorption, water permeability and gas permeability are available. Many of these are invasive due to their destructive nature and also measure properties against which compliance cannot be reliably determined.

The major limitation identified for most penetrability methods is he influence which moisture has on the results obtained.

To overcome this, two broad options have been identified, including preconditioning the surface by forced drying and independent measurement of moisture content prior to testing.

The second option is preferable as there is no way of knowing the exact extent of drying and the residual moisture profile if the surface drying option is used. An alternative approach in the proposed vacuum drying technique developed by Dhir et al [(14)] which overcomes the difficulty of the uncertain moisture content of the in-situ concrete.

Taking into consideration the above requirement, the preferred test method for surface durability is a modified Initial Surface Absorption Test (ISAT). This proposes the use of a guard ring located around the perimeter of the standard cap containing water at the same hydrostatic pressure resulting in Uniaxial flow using within concrete. Using this modification an mproved correlation has been found.

CONCLUSION

It is clear that compliance testing as part of concrete delivery and placement are critical to achieving long term durability performance. In this context the availability of a self regulated ready mix industry which can guarantee a supply of concrete with fresh concrete properties to meet performance specifications is the first prerequisite. Following this the critical importance of achieving cover to reinforcement cannot be overstated. Finally the quality of covercrete must be guaranteed. While there are several gaps in the availability of reliable inexpensive testing methods the simple cover meter, the available NDT testing for strength (UPV, Rebound Hammer, Pull off testing) and surface durability measurements (Sorptivity, ISAT and Figg) can go a long way to guaranteeing durable concrete and lowest life cycle cost structures.

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