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Specifying Effective Curing during Construction to Ensure Durable Concrete

Durabilité du béton par une cure efficace en cours de construction

Festlegung wirksamer Nachbehandlung für dauerhaften Beton

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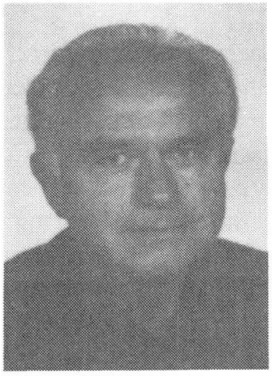


A graduate of the University of Cape Town in 1961, Gert Hoppe has been involved with the design, construction and rehabilitation of concrete bridges. He obtained an MSc Degree in 1981 for research on properties of site and laboratory concrete and has specialised in rehabilitating bridges and specifications for durable bridges.

SUMMARY

The erroneous assumption that concrete strength and durability are closely linked has now been disproved by research. A durable concrete is produced by ensuring that the mix is properly constituted, placed, compacted and cured. To ensure that durability is achieved on site, either much more rigorous supervision of the concreting must be done or tests must be developed which accurately measure the degree of durability of concrete. The proposed tests measure the oxygen permeability, water sorptivity and chloride conduction properties. The results are compared with specified acceptance criteria in accordance with required quality of cured concrete to ensure durable concrete.

RÉSUMÉ

Les récents résultats de la recherche remettent en cause l'hypothèse largement admise d'une étroite liaison entre résistance et durabilité. Pour qu'un béton soit durable, il est indispensable que la composition, la mise en oeuvre, le vibrage et la cure soient irréprochables. Il faut une surveillance rigoureuse des opérations de bétonnage et des procédés adéquats d'essais, afin de garantir la durabilité désirée. Les méthodes proposées servent à mesurer la perméabilité à l'oxygène, le pouvoir d'absorption d'eau et la conductibilité vis-à-vis des chlorures. Les résultats d'essais sont à comparer avec les critères de réception définis en fonction de la qualité de la cure et de la durabilité du béton.

ZUSAMMENFASSUNG

Die Annahme, dass Festigkeit und Dauerhaftigkeit von Beton eng miteinander zusammenhängen, wird jetzt von neueren Forschungsergebnissen in Frage gestellt. Um die Dauerhaftigkeit auf der Baustelle zu sichern, muss der Betoniervorgang sehr viel strenger überwacht werden, zusammen mit der Entwicklung geeigneter Testverfahren zur genauen Bestimmung der Dauerhaftigkeit. Die vorgeschlagenen Verfahren messen die Sauerstoffdurchlässigkeit, das Wasserabsortionsvermögen und die Chloridleitfähigkeit von Beton. Die Ergebnisse werden zu definierten Annahmekriterien für die Qualität der Betonnachbehandlung in Beziehung gesetzt.

1. INTRODUCTION

The erroneous assumption that concrete strength and durability are closely linked together has long been espoused by Engineers even though research has largely disproved the connection. Strength certainly does have a role to play in producing durable concrete but specifications which are strength criteria alone may result in concrete of poor durability characteristics. A durable concrete is produced by ensuring that the mix is properly constituted, placed, compacted and cured.

2. EFFECTS OF CURING ON CONCRETE PROPERTIES

2.1 Compressive Strength

Most of the early research into curing of concrete focused on the effect that curing has on compressive strength. This was mainly due to the emphasis Engineers placed on strength as the most important material property of concrete. Research on the effect of curing on strength development has been useful to highlight trends resulting from different curing histories. Continuous moist curing was found to provide higher long-term strength than concrete which was air cured at any stage.

Little research data is available concerning the effect of curing on compressive strength of concrete structures on site. Further work needs to be done in this regard as data available from laboratory investigations of curing can only be used for comparative purposes. The effect of curing on the overall structural integrity of the concrete structure needs to be quantified.

2.2 Durability

2.2.1 Durability Parameters

The most significant concrete parameters defining the resistance of concrete to deterioration are the permeation characteristics of the surface and near-surface concrete. Not only does the cover concrete interface and react directly with the environment but it is the concrete which has the poorest quality and most likely to suffer [1][2]. Permeation can be divided into three distinct but connected transportation phenomena for moisture vapour, dissolved ions, gases and aqueous solutions :

PERMEATION

Absorption   Diffusion   Permeability

Absorption describes the process by which concrete takes in a liquid, normally water or aqueous solution, by capillary attraction. The rate at which water enters is termed absorptivity (or sorptivity). The moisture may contain dissolved salts, such as chlorides or sulphates and dissolved gases, such as oxygen, carbon dioxide and sulphur dioxide. The transportation of ions is therefore often a combination of absorption and diffusion.

Diffusion is the process by which a vapour, gas or ions can pass through concrete under the action of a concentration gradient. Diffusivity defines the rate of movement of the agent and is the mechanism by which carbonation occurs and also characterises the ingress of chlorides and other ions. It is, therefore, closely linked to reinforcement corrosion problems.

Permeability is defined as the flow property of concrete which quantitatively characterises the ease by which a fluid or gas will pass through it, under the action of a pressure differential. This contrasts with absorption and diffusion which are caused by a concentration differential.

Durability properties investigated include permeability, sorptivity, carbonation, chloride diffusion.

2.2.2 Permeability

Permeability testing of concrete has long been recognised as an effective way of assessing the potential durability of concrete which is governed more by its porosity and permeability than by bulk properties such as strength and elastic modulus. Researchers have shown that the oxygen permeability of water cured concrete was significantly lower than similar air cured concrete.

2.2.3 Water absorption

Water absorption is a useful durability parameter as often the predominant mechanism causing water movement into concrete is capillary action rather than an applied water head. Researchers have reported that concrete that was not cured at all had up to ten times the surface absorptivity of well cured concrete. Extending the duration of water curing was found to reduce the amount of water absorbed by concrete. Intermittent water spraying was found to be far less effective for curing concrete than full immersion curing.

2.2.4 Water sorptivity

Water sorptivity is a measure of the rate of movement of a water front through a porous medium such as concrete, due to capillary action. It may therefore be considered to be very similar to water absorption. Continuous water curing was found to produce concrete with much lower sorptivity than uncured concrete. Similar reductions of sorptivity were found for concrete of higher compressive strength and concrete made with water reducing agents.

2.2.5 Chloride diffusion

Chloride initiated reinforcement corrosion is a major form of concrete deterioration in the marine environment. The penetration of chlorides into concrete is largely due to ionic diffusion and water movement caused by wetting and drying cycles. The speed at which these processes take place is dependent upon the quality of the cover concrete and research has shown that well cured concrete has significantly lower chloride contents than similar uncured concrete.

2.2.6 Carbonation

Carbonation of concrete can cause corrosion of reinforcement due to the resulting reduction of concrete alkalinity around the steel. Carbonation is determined by the rate of gaseous diffusion of atmospheric carbon dioxide into the concrete pore structure. Researchers using an accelerated carbonation test showed that the depth of carbonation decreases with increasing length of curing. It was found that curing for up to seven days produced dramatic reductions in carbonation but very little beyond seven days.

2.3 Different Cement Binders

Comparisons between OPC concrete and other types of concrete containing mineral extenders such as fly ash and GGBS are complicated by how the original mix design was formulated. Comparisons can be made on strength replacement, replacement plus addition or addition only.

2.3.1 OPC concrete

Most of the research on curing has focused on OPC concrete which is the most commonly used cementitious binder. The effect of curing on other cementitious binders has more recently received attention as these materials have gained greater acceptance in construction. Pozzolanic materials such as fly ash and granulated slag have traditionally been considered more vulnerable to poor curing practice as the pozzolanic reaction is generally slower than that of normal cement hydration. Research on the sensitivity of other cementitious binders to curing has generally been done by comparing their performance to that of similar OPC concrete.

2.3.2 Fly ash concrete

Researchers have investigated the effects of curing on durability properties of fly ash concrete. Durability indexes investigated were oxygen permeability and water sorptivity. Results indicated that fly ash concrete was more affected by curing than OPC concrete when oxygen permeability and sorptivity results were compared. Of more significance however was the fact that the fly ash concrete still had lower values of oxygen permeability and sorptivity than similar OPC concrete.

2.3.3 Slag concrete

Researchers using the oxygen permeability and sorptivity durability index tests to measure the ability of slag concrete to withstand poor curing practice and found that slag concrete was more vulnerable to poor curing than similar OPC concrete.

2.4 Concrete Structures in Service

Very little research has been done on the effect of curing on concrete structures in service. Curing of concrete has been investigated almost entirely by laboratory based research using small concrete specimens exposed to static environmental conditions. More field data is required to quantify the effect of poor curing on the durability performance of concrete in service.

There is a widely held view that the lack of durability of many concrete structures is due to inadequate curing but researchers have shown that there are hardly any examples in the technical literature to substantiate this opinion. This is because concrete deterioration is invariably caused by a combination of different factors, which make assessing the role of curing difficult. Other construction processes which can be detrimental to concrete durability include inadequate compaction, over vibration, low cover to reinforcement and bad design leading to excessive cracking. Poor curing may be responsible for more concrete deterioration than is generally recognised but the means of determining the effect of poor curing do not exist.

3. RECOMMENDATIONS FOR ENSURING GOOD CURING PRACTICE

These recommendations may be classified as being either prescriptive or performance methods.

Prescriptive Methods

These have been the traditional methods used to date to ensure adequate curing. Many people believe if the curing method is practical and strictly enforced on site there should not be a problem. Finding a practical curing method and guaranteeing that it is adhered to on site is not so simple and some argues that curing compounds ensure the most effective curing in many situations as other curing methods are difficult to maintain and supervise, while others do not recommend any particular curing method but states that the curing method must be fully specified by the designer and listed separately in the Bill of Quantities.

Performance Methods

Performance methods have recently been developed to assess the effectiveness of the curing method chosen. Methods include in-situ tests of surface quality and testing of samples extracted from the structure for later testing in the laboratory. As yet no test has been developed which has enjoyed any widespread acceptance in the construction industry.

The advantage of performance testing of concrete is that the contractor is free to choose the curing method most suitable for his circumstances provided the concrete achieves the compliance criteria. The difficulty of performance testing is reaching agreement with all parties about the performance method chosen and ensuring the test is suitable and reproducible on site. More research and testing is required in this area before performance testing of concrete curing can become viable. Considerable research effort is being focused on the problem and positive results from this work should become available for practical implementation in the near future.

4. METHODS OF DEFINING DEGREE OF POTENTIAL DURABILITY

4.1 Introduction

To determine the degree of durability of a concrete it is necessary to test the material for properties such as water absorption, chloride diffusion and permeability. Obtaining absolute figures on these material properties is difficult because the exposure and material conditions are constantly changing. Index tests overcome these problems by preconditioning the sample initially and standardising the exposure conditions. The test therefore simulates the transport mechanism causing deterioration and produces results which are reliable and can be used for comparative purposes. This can be done by correlating durability index results with the long term performance of concrete in a particular environment.

4.2 Laboratory-based Tests

Extracting samples from concrete structures and conducting durability tests in the laboratory has the advantage of being able to condition the concrete before testing and test in a controlled environment.

Laboratory based tests are generally more reliable than insitu tests but results can only be used as an indication of the likely durability performance of the structure. Care must be taken during sampling to ensure that the set of samples taken are representative of conditions on site.

4.2.1 Oxygen Permeability

The coefficient of permeability is controlled by the size and continuity of pores, the presence of cracks and microcracks and transition zone defects between aggregate and cement paste. Good quality aggregate is usually sufficiently dense to have little effect on the overall permeability of the concrete. Testing for permeability has widely been recognised as a method of defining the degree of durability of concrete. The tests may be broadly divided into either through-flow, penetration and falling head tests. The falling head permeameter developed by Ballim [3] measures the coefficient of permeability quickly and economically. The test subjects oven-dried concrete samples to oxygen gas under pressure and the pressure drop caused by oxygen diffusing through the concrete is monitored. Preconditioning the concrete by oven-drying at 50°C for seven days does cause some microstructural damage but the conditioning tries to ensure that all concrete is tested from the same start point.

Permeability is generally acknowledged to be sensitive to the type of curing applied to concrete. Results from the oxygen permeability test show that dry cured concrete was more permeable than similar concrete which had been moist or wet cured. The difference in the coefficients of permeability for dry and wet cured concrete could be as high as one order of magnitude.

4.2.2 Water Sorptivity

Sorptivity is defined as the rate of movement of a water front through a porous material under capillary action and due to the mechanism of water absorption, sorptivity is dependent on the initial water content of concrete, the temperature and the type of fluid being used.

Ballim [4] developed a simple sorptivity test based upon Kelham's method. The test is performed on cored concrete samples which are oven-dried and then exposed to water on the top surface to allow unidirectional water absorption. By measuring the weight of water absorbed with time, the progress of the water front through the concrete and therefore the sorptivity can be determined.

Sorptivity is sensitive to the type of curing performed on concrete, with wet curing producing the lowest sorptivity values.

4.2.3 Chloride Conduction

Aggressive agents such as chlorides are generally transmitted by ionic diffusion particularly at depths greater than 20 mm where water absorption effects are negligible.

Ionic diffusion depends upon the concentration gradient driving the process, the degree of saturation of the concrete pores and the physical and chemical resistance of the concrete to the diffusion process. Diffusion tests are usually accelerated in the laboratory by applying a potential difference across the sample, increasing the concentration gradient or using a combination of both. Most accelerated diffusion tests take several days to run as the concrete needs time to reach steady state conditions before diffusion measurements can be taken. This time delay can result in inaccurate readings especially when rating curing efficiency as the cement may continue hydrating during the test. The chloride ions also react with the products of hydration during the test which effectively changes the pore structure.

Streicher [5] has developed an extremely rapid chloride conduction test which takes only a few seconds to run once the samples have been preconditioned by vacuum saturating with a concentrated salt solution. Theoretically it is possible to relate chloride diffusion to chloride conduction so that the method can be used as an index test. Experimental work has been done on the sensitivity of the chloride conduction test to the type of curing and was found to be sensitive to different types of curing. The test has also been found to be sensitive to changes in pore structure due to mineral extenders such as fly ash and slag.

4.3 Insitu Tests

A number of insitu tests have been developed to assess the durability of concrete structures in service. These tests are generally non-destructive in nature but may involve some drilling of concrete either to mechanically fix the apparatus or to prepare a hole through which the concrete will be tested. The ISAT test was originally developed to test concrete roof tiles but has been widely used and modified. The test measures the rate at which water is absorbed into concrete by clamping a perspex cap on the concrete surface. A drawback of the test was the effect of surface coatings and carbonation which affected the reliability of the results. To overcome this the Figg test was developed which uses a 5.5 mm diameter hole to measure water absorption or gas diffusion through the cover concrete. Many modifications of the Figg test were produced including the Covercrete Absorption Test (CAT) and the CLAM [6] test. All of these insitu tests were found to be significantly affected by the original moisture content of the concrete. Even though corrections can be applied to the results to allow for the variable moisture content, determining the actual moisture value insitu is unreliable. A variety of methods were proposed to overcome the problem and now Dhir et al [7] proposed a preconditioning process where the concrete was vacuum dried using a portable vacuum pump immediately before testing.

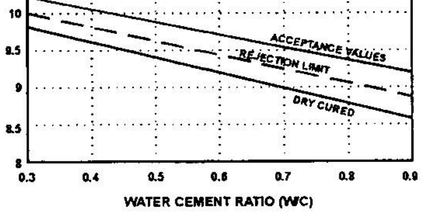
5. ACCEPTANCE CRITERIA FOR DEGREE OF DURABILITY ACHIEVED ON SITE

5.1 Introduction

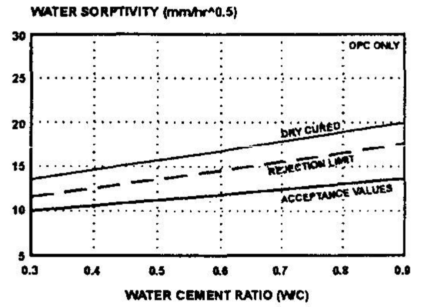
Based on the present state of research, it is proposed to measure the following properties using laboratory based tests, where the age of coring the concrete is 28 days, which implies that the concrete is tested at 35 days to allow for time taken to condition the samples.

In order to achieve acceptable durability the contractor's method of curing must ensure that the values for the oxygen permeability, water sorptivity and chloride conductivity and of the site concrete fall below the following graph values, which need to be established per region and country [1][8].

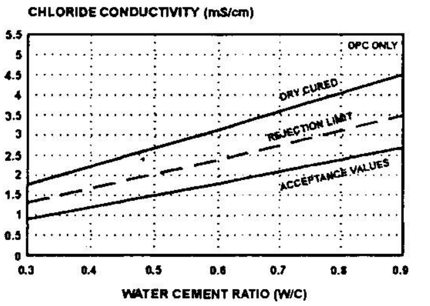
5.2 Oxygen Permeability



5.3 Water Sorptivity



5.4 Chloride Conduction



6. CONCLUSIONS

The present approach to ensuring durability of concrete structures is too haphazard to guarantee achieving the design life. Durability can only be confidently predicted once relevant material properties are specified and achieved during construction. Tests are needed to measure these material properties affecting durability and practical implementation of the tests into contract specifications must be done. Defining the degree of durability of concrete is complicated by the fact that different environments demand differing durability characteristics from concrete structures. No single test would adequately measure concrete durability for all forms of service functions and types of deterioration. It is therefore necessary to develop a number of tests and to use that test most appropriate to the exposure and service conditions for the structure in question. More data is required before any of the tests can be used as part of the project specification of a contract. This type of approach would need to be run in tandem with more traditional methods of ensuring concrete curing to assess the practical problems which might arise in applying the tests on site.

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