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Use of Durability Index Tests for the Assessment and Control of Concrete Quality on Site

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ABSTRACT: An investigation into the feasibility and practicality of performing oxygen permeability, water sorptivity and chloride conductivity index tests on actual structures is presented. The tests assist in defining the potential durability of concrete and could form the basis of construction specifications for the assessment and control of the quality of cover concrete.

The tests were used to assess concrete produced at several different construction sites in the Cape Peninsula area. Site-prepared cubes, as well as cores taken on location from the actual structures, were tested, as were several sets of ready-mixed concrete.

The results indicate that the characteristics of the mix materials, other than the cement, can have a noticeable influence on index results. It was also found that the variability of concrete from a reputable ready-mix plant is lower than that for site-batched concrete. Cement type has a significant influence on results, particularly for chloride conductivity. As was expected, the indexes of samples cored from actual structures, were generally poorer than those of cubes water-cured for 28 days, indicating that placing and curing practices on site may impair the potential durability of concrete.

In general, poor correlation was found between the indexes of the wet-cured cubes and of the actual structures, revealing that even with a good combination of high quality mix constituents, poor quality can result on site due to indifferent construction practices. Nevertheless, with due care, site indexes can equal or even surpass those cubes cast under controlled conditions. The variability of site results was sufficiently low to suggest that the durability index approach can be successfully applied on site to assist in producing quality concrete.

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USE OF DURABILITY INDEX TESTS FOR THE ASSESSMENT AND CONTROL OF CONCRETE QUALITY ON SITE

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ABSTRACT

An investigation into the feasibility and practicality of performing oxygen permeability, water sorptivity and chloride conductivity index tests on actual structures is presented. The tests assist in defining the potential durability of concrete and could form the basis of construction specifications for the assessment and control of the quality of cover concrete.

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The results indicate that the characteristics of mix materials, other than the cement, can have a noticeable influence on index results. It was also found that the variability of concrete from a reputable ready-mix plant is lower than that for site-batched concrete. Cement type also has a significant influence on results, particularly for chloride conductivity. As was expected, the indexes of samples cored from actual structures, were generally poorer than those of cubes water-cured for 28 days, indicating that placing and curing practices on site may impair the potential durability of concrete.

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The variability of site results was sufficiently low to suggest that the durability index approach can be successfully applied on site to assist in producing quality concrete.

1 INTRODUCTION

Three durability index tests have been developed recently by South African researchers, Alexander and Ballim (1993), Ballim (1993), Alexander, Mackechnie and Hoppe (1995), Streicher and Alexander (1995), and Mackechnie (1996), namely the

- **oxygen permeability test,**
- **water sorptivity test, and**
- **chloride conductivity test.**

Each test measures a different transport property of fluids or ions through the cover layer of concrete. The resistance of cover concrete to these transport processes governs the deterioration of concrete and embedded steel and may therefore define the potential durability of concrete. The tests have proved sensitive to durability-related aspects of concrete construction, such as materials, compaction, and curing.

The three index tests have been developed and proved in the laboratory, but have not been extensively performed on concrete of actual structures under typical site conditions. It was considered essential to determine if it would be possible to use the index tests to determine the quality of site concrete. If the tests provide reliable results, a basis would be created for producing specifications that would ensure durability more directly, using permissible index values for concrete elements, Alexander (1997). As the index values would provide reproducible measures of concrete quality, provision for payment could include the requirement that the site concrete gives acceptable index results.

Before the tests can be used in practice, however, it is necessary to determine the range of results and degree of variability that can be expected when the durability index tests are applied to site concrete. The construction process on

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His teaching and research interests are in the area of concrete properties and structural behaviours and he has published papers both in South Africa and abroad. He also acts as a specialist consultant to industry and the profession on concrete materials problems.

Gerhard Maritz

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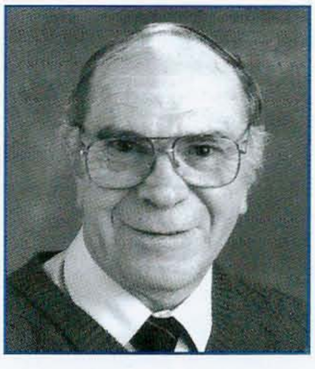


the Imperial College, London. Until his appoinment as a senior lecturer in Civil Engineering at the University of Stellenbosch he worked in railway maintenance and construction, road design and concrete quality control on a large dam construction project. At Stellenbosch he has been involved in teaching and research in basic strength of materials, structures and materials with particular emphasis on concrete. He is the author and co-author of several papers. Gerhard Maritz is a member of the Concrete Society and is at present the President of the Society.

site differs substantially from mixing, moulding and curing concrete in a laboratory, where the quantity and quality of the constituent materials as well as the concrete-making process itself can be controlled rigorously and the environmental conditions kept constant. Because of this, site concrete is expected to have inferior durability qualities and greater variability than laboratory concrete, but until the durability index tests have been applied on site concrete, these effects cannot be quantified. A database of durability indexes of site concrete is therefore required. Once in existence and of sufficient extent, such a database could be used to specify limiting values to the indexes in construction specifications.

A database of site concrete results could also be used for prediction purposes. Although the durability index results might give valuable information regarding the durability characteristics of concrete, they must be correlated with actual performance in order to utilise their full potential. The ideal would be that aspects such as the rate of carbonation, chloride ingress etc. of structures for which the durability index values are known, be measured at regular time intervals in future. Correlations could then be drawn between the measured index values at relatively early ages (weeks to months) and the long-term performance of the structures (years to decades). These results would ultimately serve the purpose of assisting engineers in deciding what concrete to use in a given environment for an optimum service life.

This study was therefore undertaken with the following objectives.

- To measure and present durability index results of actual site concrete, and evaluate the influence of construction methods, design parameters and environment on the index values.
- To measure and present the durability index results of several batches of ready-mixed concrete and compare them with the site results.
- To use the results obtained to assess whether the index tests could assist in controlling concrete quality on site.

2 THE DURABILITY INDEX TESTS

The durability index tests have been covered elsewhere, eg. Alexander, Mackechnie and Ballim (1999), but a brief summary is given here for completeness.

2.1 The water sorptivity test

Sorptivity is defined here as the rate of movement of a wetting front through a porous material. The water sorptivity test, Ballim (1993), in its modified form, Alexander et al (1999) involves the uni-directional absorption of water into one face of a pre-conditioned concrete disc sample. At predetermined time intervals the sample is weighed to determine the mass of water absorbed. The sample is then vacuum-saturated with water and the mass determined. The sorptivity of the material is determined from the plot of mass of water absorbed versus square root of time. The lower the water sorptivity index, the better is the potential durability of the concrete.

Mackechnie (1996) performed water sorptivity tests on three different grades of CEM I, fly ash and slag concrete. He found that absorption rates of concrete reduced with increasing grade of concrete and duration of moist curing. Wet curing and moist curing produced similar results while dry-cured concrete had significantly higher sorptivity values. He stated that the sorptivity test measured a surface property and should therefore be sensitive to early-age drying effects which influence the microstructural porosity gradients in the concrete. Differences in sorptivity values for wet and dry cured concrete were between 25 % and 70 %, indicating that the test method may be effective in assessing curing effectiveness on site. According to Ballim et al (1994) the sorptivity test is sensitive to the gradation of concrete quality with depth from the surface.

Ballim et al (1994) and Streicher (1996) both indicated that the test is sensitive to the extent of curing, especially during the first seven days after casting. Ballim noted that for moist curing periods longer than 3 days, increase in compressive strength above 30 MPa had only a small effect in decreasing the sorptivity of concrete. According to Ballim the sensitivity of the water sorptivity index of CEM I concrete to the effects of initial moist curing decreased as the water:cement ratio decreased, and with 28 days of moist curing, the sorptivity of surface concrete became almost insensitive to changes in the normal range of water:cement ratio.

2.2 The oxygen permeability test

The oxygen permeability test, Ballim (1993), involves a falling head permeameter in which oven-dried (50° C for 7 days) concrete samples, generally 68 mm diameter and 25 to 30 mm thick, are placed in rubber collars which are secured on top of a permeability cell. The cell is filled with oxygen to a pressure of 100 kPa before being isolated, after which the pressure decay is monitored, typically for several hours. The Darcy coefficient of permeability, k, may be determined from the slope of the line produced when the log of the ratio of initial pressure to decaying pressure is plotted against time. The index is then defined as

Oxygen permeability index = -Log(k) (1)

Oxygen permeability indexes are logarithmic values and range generally from 8 to 11, i.e three orders of magnitude; the higher the index, the less permeable the concrete.

Mackechnie (1996) performed the oxygen permeability test on three different grades for each of CEM I, fly ash and slag concrete as was done for the water sorptivity test. He found that the oxygen permeability indexes increased, (i.e. improved quality) with increasing grade of concrete and extent of moist curing. Fly ash and slag concrete were less permeable than CEM I concrete when well cured, but were more permeable when dry-cured. He stated that the oxygen permeability index is more dependent on the amount and continuity of larger pores or channels in the concrete where most of the flow will occur, and which are likely to have been caused by poor compaction or bleeding. He indicated that the test is less sensitive to the finer capillaries and observed that the oxygen permeability index did not reflect the inherently finer pore structure which is characteristic of fly ash and slag concretes.

Ballim et al's (1994) results showed that the oxygen permeability of low-strength concrete was much more sensitive to the duration of wet-curing than high-strength concrete. The oxygen permeability index of grade 35 CEM I concrete increased from 8.50 to 10.16 when duration of wet-curing increased from 1 to 28 days, while that of grade 55 CEM I concrete only increased from 9.43 to 10.44. The same trend was revealed in increasing grades of CEM I/fly ash concrete. Streicher (1996) also remarked on the sensitivity of oxygen permeability indexes to curing, observing that the sensitivity to curing reduced with time of moist curing and decrease in water:cement ratio. Ballim et al (1994) noted that a particular index value could be obtained either by extending the duration of curing of low strength concrete or by decreasing the water:cement ratio in the event that curing was likely to be minimal or ineffective.

2.3 The chloride conductivity test

Chloride diffusion is the main process by which chloride enters concrete in a marine environment. Streicher recently developed a rapid chloride conductivity test at the University of Cape Town in which virtually all ionic flux occurs by the process of conduction due to a 10 V electrical potential difference between the two faces of a sample, Streicher and Alexander (1995) and (1999). The chloride conductivity apparatus consists of a two-cell conduction rig. Each cell contains a 5M NaCl solution so that there is no concentration gradient across the sample and chloride migration is the result of conduction from the applied potential difference. The cylindrical concrete sample is pre-conditioned by vacuum saturating it with a 5M NaCl solution. Diffusion and conduction are related by Einstein's relationship, thus allowing the conductivity test to be used as an index of concrete diffusivity.

In the chloride conductivity test, chloride ions move through all pores of sufficient size, without favouring the larger pores as with the permeation process. The chloride conduction test therefore provides a good indication of the overall diffusivity of the material, the test being sensitive to changes in the pore structure and cement chemistry which might appear to be insignificant when using the permeation process, Mackechnie (1996). Typical chloride conductivity index values for concrete range from very poor (>3 mS/cm) to excellent (<0.75 mS/cm); the lower the index the better the potential durability[1] of the concrete.

Mackechnie (1996) observed that 28-day indexes reduced with increasing concrete grade, but were more affected by the duration of curing and, in particular, the type of binder. When properly cured, the addition of fly ash or slag had the effect of refining the pore structure and altering the chemistry of the concrete, and the chloride conductivity test was found to be extremely sensitive to such changes.

3 DETAILS OF CONCRETE ELEMENTS AND SAMPLING PROCEDURE

The index tests were used to assess concrete produced at several different construction sites in the Cape Peninsula area. Site-prepared cubes as well as cores taken on location from the actual structures were tested. Several sets of cube samples of ready-mixed concrete were also tested. Because of the more specialist nature of a large ready-mixed concrete batching plant, it was expected that the degree of control over the

[1] In the context of this paper, the potential durability of concrete can be defined as the degree of resistance of the cover concrete to the conduction of chlorides permeation of oxygen and absorption of water, as indexed by the tests described in the paper.

concrete-making process would be better at a ready-mixed plant. The concrete was therefore expected to be more consistent, have a lower degree of variability and be of better quality than equivalent mixes from a typical on-site plant.

3.1 Site Work

Samples for testing were obtained from 14 concrete elements under construction on 6 construction sites during the course of 1996. The samples were taken only from elements that were to be left exposed to the outdoor environment without being coated, for the lifetime of the structure. A set of 150 mm cubes was also prepared from each of the mixes on site. The cubes were wet-cured at 23 °C for 28 days and the strength and durability index results used as controls to determine the influence of concrete quality and strength on the site results in comparison with the influence of construction practice. Cores of 68-mm diameter were drilled from the cubes and the actual concrete elements at 28 days after casting. The cores from the concrete elements were taken from a single area not larger than 1 m^2. Samples 25 mm thick were prepared from the outer 5 to 30 mm of a core. From each element and set of cubes, three samples were prepared for the chloride conductivity test and four samples for the water sorptivity and oxygen permeability tests. In this work, a chloride conductivity result is the average of three individual test determinations, and an oxygen permeability and a water sorptivity result the average of four individual test determinations.

Table 1 (below) summarises the concrete mixes from the different sites, while Table 2 gives the average environmental conditions for the first 7 days after casting (from Cape Town International Airport) and the curing regimes and compaction methods used.

Table 1: Concrete mixes used at the various sites

Element	Specified 28-d characteristic strength (MPa)	Total binder(1) (kg/m³)	Fine aggregate(2) (kg/m³)	Coarse aggregate(3) (kg/m³)	Water (l/m³)	Admix-ture(4) (l/m³)	Water: binder ratio	Slump (mm)
1A	30	280	845	1200	160	-	0.57	50
1B	25	280	845	1200	165	-	0.59	30
2A	30	316	1224	980	177	-	0.56	75
3A	40	346	720	1200	160	2	0.46	35
3B	40	346	720	1200	160	2	0.46	65
4A	30	303	754	1130	158	0.92	0.52	90
4B	30	303	758	1130	154	0.92	0.51	160
4C	30	303	758	1130	154	0.92	0.51	75
5A	45	420	643	1160	182	1	0.43	90
5B	45	420	643	1160	182	1	0.43	-
6A	25	320	720	1200	160	1	0.5	55
6B	25	320	720	1200	160	1	0.5	50
6C	25	320	720	1200	160	1	0.5	60
6D	25	337	762	1140	162	1.17	0.48	75

Notes:

1 Binder was CEM I, except for element 5A where a 75/25 CEM I/FA blend was used.
2 Fine aggregate was generally natural pit sand, blended with a dune sand on occasions.
3 Coarse aggregate was generally 19 mm crushed greywacke, except elements 2A, 5A and 5B where a 19 mm crushed quartzite from the Western Cape was used.
4 Admixtures were either plasticizers or plasticizers/ air entrainers.

As can be seen in Table 2, the testing on sites 1 to 4 and 5A occurred under typical summer conditions, with mild average ambient temperatures and relatively low humidity. Testing on sites 5B and 6 occurred under typical winter conditions, with lower temperature, rain and higher relative humidity.

Table 2: Average environmental conditions at the various sites for the first 7 days after casting (data from Cape Town International Airport)

Element	Casting date	Type of element	Ave. air temp. (°C)	Ave. rel. humidity (%)	Total rainfall (mm)	No. of days from casting to occurrence of rainfall (d)	Casting and curing regime
1A	22/01/96	Column	21	66	1.8	2	24 h in forms; curing compound sprayed on 1 h after stripping.
1B	12/02/96	Wall	20	66	27.6	4	48 to 54 h in forms; curing compound sprayed on 0 to 2½ h after stripping.
2A	24/01/96	Slab	21	64	0.2	7	Covered with sand 24 h after casting; sprayed with water 4 times daily for next 9 days.
3A	25/01/96	Wall	21	65	0.2	6	17½ h in forms, covered with wet hessian immediately after stripping.
3B	07/02/96	Wall	21	72	27.6	7	23 h in forms, not actively cured.
4A	05/02/96	Slab	22	69	0	-	Sprayed with curing compound 1 to 2 h after casting.
4B	18/03/96	Slab	19	74	0	-	Sprayed with curing compound 1 to 2 h after casting.
4C	11/04/96	Slab	17	67	4.8	4	Sprayed with curing compound 1 to 2 h after casting.
5A	15/02/96	Coping wall	21	68	0	-	21½ h in forms. Top sprayed with curing compound 2 h after casting, sides directly after stripping.
5B	15/03/96	Coping wall	14	83	0	-	24½ h in forms. Top sprayed with curing compound 2 h after casting, sides directly after stripping.
6A	24/07/96	Wall	11	80	16.8	2,3,4,5	24 h in forms, curing compound applied immediately after stripping, washed off by rain.
6B	02/08/96	Wall	12	77	48.8	1,4,5,7	72 h in forms.
6C	03/08/96	Wall	12	75	32.8	0,1,4,5	9 days in forms
6D	07/08/96	Wall	11	74	32.8	0,1,4,5	5 days in forms

Notes:

All the vertical elements were compacted by means of poker vibrators.

For the slab, element 2A, concrete was cast directly into position, and shovels and poker vibrators used to compact and move it to fill whole slab section. The concrete was levelled by working a wooden roller of approximately 10 cm diameter over it.

For the other three slabs, element 4A, B & C, the concrete was placed onto a 10 m long conveyor belt which carried it to final position. Shovels and poker vibrators were used to move and compact the concrete. Final compaction and levelling-off were done by means of a screed vibrator.

For elements 6B to 6D the curing advantages that might have been gained from rain were probably not realised due to long periods in the forms.

3.2 Ready-mixed concrete

Nineteen sets, each comprising seven 150 mm concrete cubes, were made on location at various construction sites to which the ready-mixed concrete was delivered. All ready-mixed concrete originated from a single ready-mix plant of a reputable manufacturer. The cubes were demoulded 24 hours after casting and wet-cured at 23°C for 28 days after which the compressive strength was determined and samples were cored for the durability index tests.

The concrete mixes could be divided into three groups: mixes 1 to 8 were 25 to 30 MPa CEM I/CSF containing 10 % silica fume; mix 9 was a 25 MPa CEM I-only mix; and mixes 10 to 18 were of grades 40 or 50 MPa, using LASRC (low-alkali sulphate resisting portland cement).

Table 3: Details of the ready-mixed concrete

No	Casting date	Specif. 28 d charact. strength (MPa)	CEM I or LASRC (kg/m³)	Dry mass of silica fume (1) (kg/m³)	Water (l/m³)	Fine agg. (2) (kg/m³)	Coarse agg. (3) (kg/m³)	Admix. (4) (ml/m³)	w:b ratio
			CEM I						
1	22/1/96	30	230	13.8	147	912	1140	472	0.60
2	23/1/96	25	214	10.8	150	893	1140	756	0.67
3	19/2/96	25	274	11.4	156	873	1140	805	0.55
4	22/2/96	25	221	11.4	152	865	1160	13	0.65
5	26/2/25	25	230	12.0	155	870	1140	827	0.68
6	04/3/96	30	257	15.0	158	873	1157	508	0.58
7	02/4/96	25	258	16.2	163	856	1153	499	0.59
8	06/5/96	25	264	13.8	180	786	1126	537	0.65
9	15/5/96	25	297		168	637	1132	740	0.57
			LASRC						
10	24/7/96	40	306		155	793	1130	1072	0.51
11	24/7/96	50	365		148	705	1170	1277	0.41
12	24/7/96	50	430		163	856	960	1505	0.38
13	25/7/96	40	306		150	793	1130	1072	0.49
14	25/7/96	50	365		154	694	1181	1254	0.42
15	25/7/96	50	430		168	856	960	1505	0.39
16	25/7/96	50	365		149	697	1179	1270	0.41
17	25/7/96	50	430		162	856	960	1500	0.38
18	26/7/96	40	365		161	721	1164	1249	0.44
19	26/7/96	50	430		171	856	960	1505	0.40

Notes:

1 A silica fume slurry consisting of 60 % silica fume and 40 % liquids of which 95 % is water was used.
2 Fine aggregate was natural pit sand, except for mix 9 where a dune sand was used
3 Coarse aggregate was 19 mm crushed greywacke
4 A plasticizer was used as admixture

4 RESULTS OF SITE ELEMENTS AND READY-MIXED CONCRETE SAMPLES

The durability indexes of the fully wet-cured cubes of the site and ready-mixed concretes as well as the indexes of cores from the actual structures are plotted against measured 28-day cube strength in Figures 1 to 3.

Figure 1: Water sorptivity vs. compressive strength

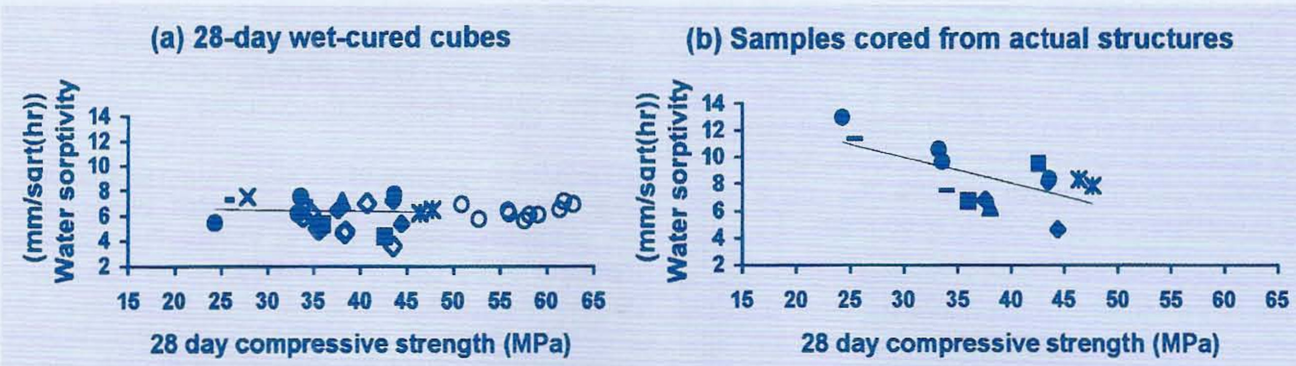


Figure 2: Oxygen permeability vs. compressive strength

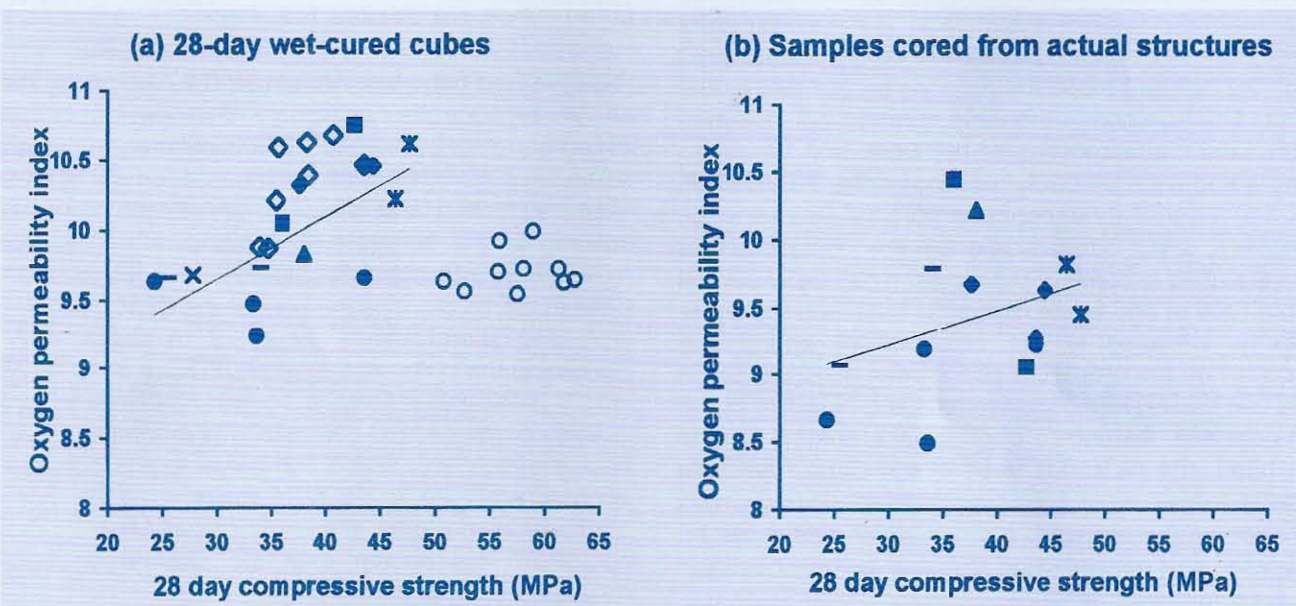
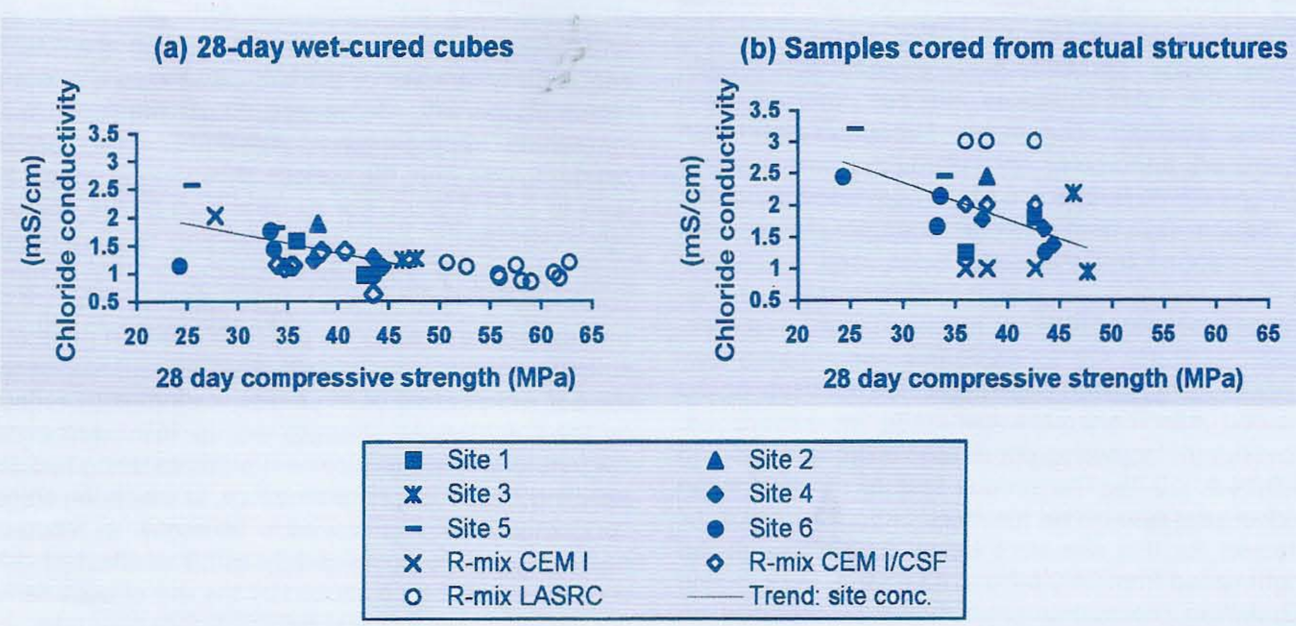


Figure 3: Chloride conductivity vs. compressive strength



4.1 Durability indexes of the 28 day wet-cured cubes

a) Water sorptivity

Site concrete: As shown in Figure 1(a), the indexes generally lie within a relatively narrow band, ranging from 4.4 to 7.8 mm/hr, regardless of the compressive strength varying from approximately 25 to 50 MPa. As the trend line indicates, the results do not decrease with increasing compressive strength, but are scattered around an average of approximately 6.5 mm/hr. This agrees with Ballim et al's (1994) findings that for moist curing periods of longer than three days increase in compressive strength above 30 MPa has only a small effect in decreasing the sorptivity of concrete.

The variation in the fully cured site-mixed results reveal that the characteristics of the materials, other than the binder, used in the mix can have an important influence on the water sorptivity indexes of wet-cured cubes. CEM I was used as binder in all except one of the mixes, and since all the cubes were compacted and cured in the same manner, factors other than the compressive strength, cement type and degree of curing have played a role. The different materials and their proportions (other than the CEM I) used in the various mixes will influence the physical characteristics of the fresh and hardened concrete and were probably responsible for the variation in the water sorptivity of concrete from the various sites. Plasticisers, which normally improve the workability of a mix, were used in some of the mixes. It can be expected that the type of aggregate used may influence the water sorptivity, because of the influence of aggregates particularly on the properties of the fresh concrete. Dune sands can cause poor cohesiveness and bleeding of the fresh concrete, leading to poor surface quality. On the other hand, the pit sands used in the Cape Peninsula generally contain more fines than dune sands and would normally give a more workable mix which can easily be compacted and possibly lead to better surface quality.

Ready-mixed concrete: Figure 1(a) shows that the binder type had a marked effect on the water sorptivity indexes of the ready-mixed concrete. The CEM I/CSF mixes follow a different trend from the LASRC mixes, achieving improved water sorptivity with increasing strength, whereas the LASRC mixes do not improve with increasing strength. The higher strength CEM I/CSF ready-mixed concretes also produced lower water sorptivity indexes than some of the site mixed concrete. The results for ready-mixed concrete were very consistent for each of the binder types used.

b) Oxygen permeability

Site-mixes concrete: In Figure 2(a) the indexes of the wet-cured site concretes generally increased, i.e. improved, with increasing compressive strength, ranging from 9.24 to 10.75. The various sets of results for the individual sites also reveal this trend except for site 6. All the results for this site were below 9.66 although the strength varied from 24.3 MPa to 43.6 MPa. Poor mixing and batching procedures were, however, reported on this site.

The different sets of site results reveal a fair degree of variability, regardless of the fact that CEM I was used except for element 5A. For example, the indexes of the 40 to 45 MPa concretes vary from 9.66 to 10.75, indicating a ten-fold difference in oxygen permeability with only 5 MPa difference in compressive strength. Again as in the case of the water sorptivity indexes, it can be argued that the characteristics of the materials, other than the cement used in the mix, might be expected to have a noticeable influence on the oxygen permeability indexes of the wet-cured cubes, primarily through their influence on the compactibility of the concrete.

Where the properties of materials, such as the type and grading of fine and coarse aggregates, plasticisers and air entrainers, differ from mix to mix, the compressive strength of 28 day wet-cured concrete has a smaller influence on the results than the "differences" in the materials. However, where the mix constituents are kept constant throughout the duration of the job, the compressive strength of the concrete correlated reasonably well with the oxygen permeability indexes of the wet-cured cubes, e.g. at sites 1, 3, 4 and 5.

Ready-mixed concrete: As for the water sorptivity indexes, under controlled conditions that exist at a ready-mixed concrete plant, and where similar aggregates and admixtures are used in all the mixes, the type of cement seems to have a large effect on the oxygen permeability indexes of the concrete. The higher strength LASRC mixes were more permeable than the lower strength CEM I/CSF mixes. The indexes of the CEM I/CSF mixes increased sharply from about 9.9 to about 10.7, by increasing the compressive strength from 34 to 40 MPa, which is approximately a tenfold improvement. The indexes of the LASRC concrete was roughly constant at approximately 9.6, which compares to site concrete of approximately 20 to 25 MPa lower strength. For any particular binder type, the ready-mixed concrete results contained less scatter than the site-mixed concrete results for oxygen permeability.

c) Chloride conductivity

Site concrete: As shown in Figure 3(a) the chloride conductivity indexes of the wet-cured cubes of the site mixes generally decreased, i.e. improved, with increasing compressive strength. The chloride conductivities from the various sites ranged widely from 0.95 to 2.56 mS/cm. For all CEM I concretes, the other mix constituents, such as coarse and fine aggregates, seem to have had less effect on the chloride conductivity results than they did on the oxygen permeability and water sorptivity indexes. In general the chloride conductivity indexes were more dependent on the cement content of the mixes, as indirectly reflected by the compressive strength results. Increased cement content relates to more cement particles being hydrated, resulting in a denser pore structure, to which the chloride conductivity test has proved to be sensitive. Since only one of the mixes contained fly ash, the effect of differences in cement type caused by the use of pozzolans, is not clearly visible in the results from site concrete.

Ready-mixed concrete: The different cement types used in the ready-mixed concrete have influenced the chloride conductivity indexes. Since both LASRC and silica fume have been reported to have poor chloride binding capacities, the test has not necessarily differentiated between the two cement types. The higher strength LASRC concrete once again performed similarly to the lower strength site and CEM I/CSF mixes. The chloride conductivity of ready-mixed concrete is not as sensitive to the compressive strength of the concrete as might be expected, probably because the strength ranges of concretes with two different cement types were rather narrow.

For low to medium strength concretes, the indexes were sensitive to changes in the compressive strength and hence cement content of the concrete. The results revealed that the chloride conductivity index is not as sensitive to mix constituents, other than cement type, as the other two tests.

4.2 Durability indexes of the actual structures

a) Water sorptivity

Figure 1(b) shows that the indexes of the actual structures generally decreased with increasing compressive strength, whereas the indexes of the wet-cured cubes were roughly constant (Fig. 1(a)). This suggests that on site, where it is impossible in practical terms to achieve the same standard of curing as in water for 28 days after casting, the concrete strength plays a noticeable role in determining the water sorptivity.

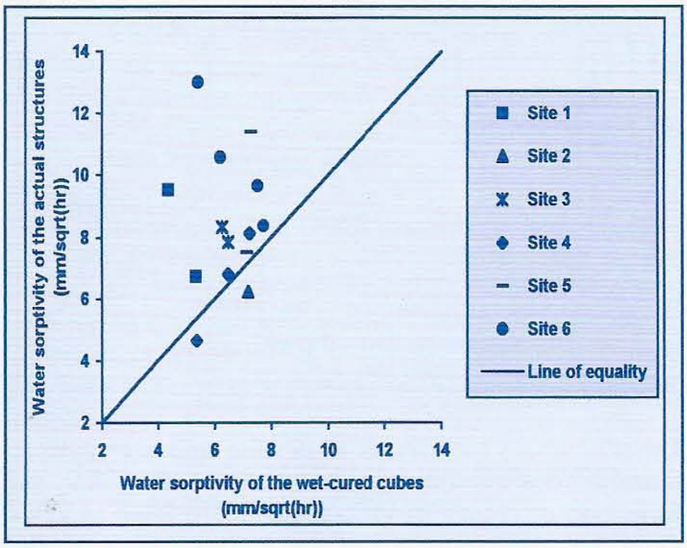
Furthermore, the results of concrete in the actual structures had more scatter than the wet-cured cube results. The higher scatter firstly reflects the lower degree of control that is present in the process of casting, compacting and curing a large structural element, in comparison with a small wet-cured concrete cube. Secondly the scatter can be ascribed to differences from site to site in the methods used to place and compact the concrete, the quality of the formwork, the way in which the surfaces were finished, and the method and efficiency of curing.

On average, water sorptivity for wet-cured concrete was 23 % less than the results for concrete in the corresponding structures. The casting, curing and other processes applied on site were therefore less effective in achieving a good, dense surface than making and wet-curing concrete cubes for twenty-eight days.

The scatter diagram in Figure 4 clearly shows that water sorptivity is sensitive to the differences between site conditions and wet-cured cube conditions, in that twelve out of fourteen water sorptivities of the actual structures were higher than those of the wet-cured cubes.

It appears that the surface quality as reflected by the water sorptivity indexes is very dependent on the method of finish of the surface. Where the concrete surface was accessible, as in the case of the concrete slabs, it was easier to achieve a good quality surface concrete by properly compacting and finishing the concrete directly after casting. In some cases surface quality of the slabs was equivalent to the surface quality of 28 day wet-cured cubes of the same concrete. In the vertical members where the surface concrete may have been poorly compacted and inadequately cured, it was also more difficult to achieve a low water sorptivity index.

Figure 4: Relationship between water sorptivities of the actual structures and the wet-cured site-cast cubes



b) Oxygen permeability

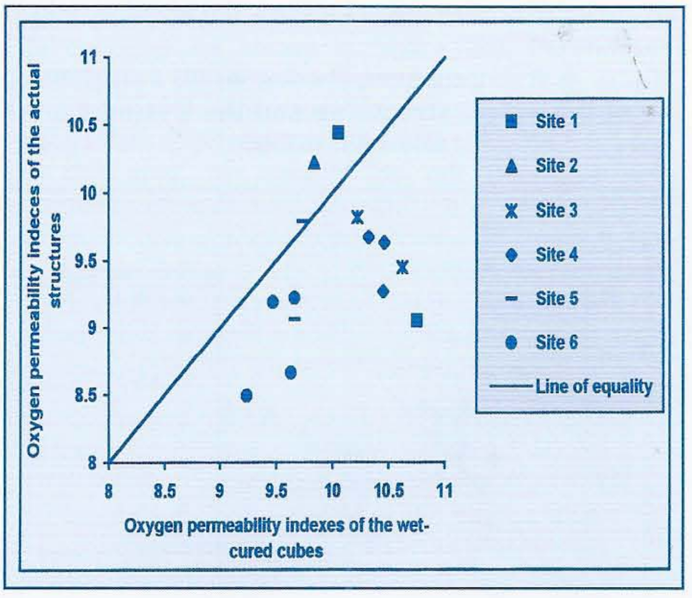
The oxygen permeability indexes of the actual structures generally increased (i.e. concrete improved) with increasing compressive strength, Figure 2(b). However, the range of values was 1.95 in comparison with the 1.51 for the wet-cured cubes. The results for the structures contained more scatter than the results for wet-cured cubes and were on average 6.5 % "poorer" (on a log scale) than the wet-cured cubes.

As was the case with water sorptivity, the oxygen permeability of the actual structures also had more scatter than those for the wet-cured cubes. This can be ascribed to the same reasons as those given for the water sorptivity results.

Figure 5 shows a scatter diagram of the oxygen permeability indexes for concrete of the actual structures versus concrete for the wet-cured cubes. In eleven out of thirteen cases the oxygen permeability indexes of the wet-cured cubes were "better" (i.e. higher) than those of the concrete in the actual structures. The average difference between the two sets is 0.7 which is equal to an average decrease of 6.5 % of the wet-cured cube results. A regression analysis was done on the data points and the value of R^2 was found to be 0.1*. There is therefore no correlation between the values for the wet-cured cubes and those for the actual structures. A good wet-cured value does not necessarily mean that a good value will be achieved on site. This confirms that good materials, proper mixing and batching techniques, and high compressive strength are not sufficient to ensure that concrete with impermeable surface is achieved on site.

*R^2 is the Coefficient of Determination and can be defined as the ratio of the explained variation to the total variation. For linear regression (i.e. the present case), the Coefficient of Determination is also the square of the Coefficient of Correlation

Figure 5: Relationship between the oxygen permeability indexes of the actual structures and the wet-cured site-cast cubes



On site, where techniques of placing and compacting, leakage from the formwork, insufficient curing, and the formation of cracks of various types are likely to influence the macrostructure of the surface concrete, the influence of factors such as the compressive strength or the properties of the mix constituents, becomes less important. It is mainly the treatment of the freshly mixed concrete from the moment that it is placed in the formwork, until after it has been cured, that is important in achieving dense, good quality surface concrete on site.

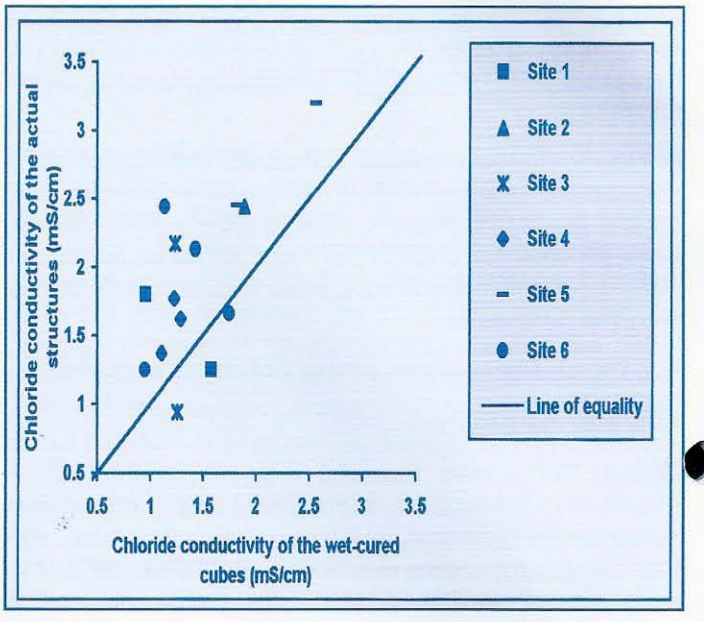
c) Chloride conductivity

In general the chloride conductivity results for the actual structures decreased with increasing compressive strength, see Figure 3(b). The results of the actual structures ranged from 0.94 to 3.2 mS/cm, while results for the wet-cured cubes ranged from 0.96 to 2.56 mS/cm. Chloride conductivity of the wet-cured cubes was, on average, 28.5 % better than those of the actual structures.

The results of the actual structures had more scatter than the results for the wet-cured cubes, because of the lower degree of control over the concrete-making and curing processes that exist on site, and the differences in placing, compaction and curing techniques that exist from site to site. It is interesting to note that the chloride conductivity results of the actual structures contained the lowest relative degree of scatter of all three tests. The chloride conductivity test is especially sensitive to changes in pore structure and cement chemistry and this low relative scatter can probably be attributed to only CEM I being used in all mixes except one.

The scatter diagram in Figure 6 shows the chloride conductivity of the actual structures plotted against the chloride conductivities of the wet-cured cubes. A regression analysis was done on the data points and the R^2 value was determined to be 0.4, indicating a poor correlation. Figure 6 confirms that the chloride conductivity test is sensitive to site effects. A good value of chloride conductivity from a wet-cured sample does not necessarily indicate that the chloride conductivity of the actual structure will also be good.

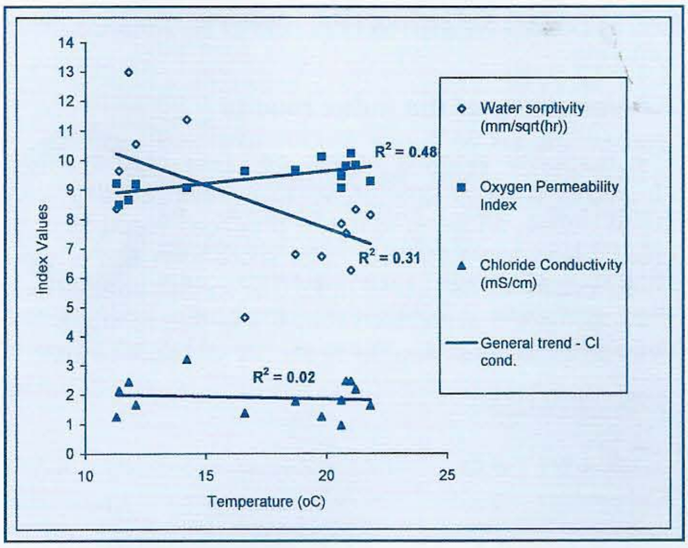
Figure 6: Relationship between the chloride conductivity indexes of the actual structures and the wet-cured cubes



4.3 The influence of environmental effects

Figure 7 shows the index values of the actual structures plotted against average air temperature for the first seven days after casting. The figure indicates that as the average air temperature increased, the durability indexes of the actual structures generally improved. As mentioned previously, summer conditions pertained to sites 1 to 5A (average temperatures between 17 and 22°C), and winter conditions to sites 5B and 6 (average temperatures between 11 and 14°C). The corresponding range of average relative humidity was:-summer conditions - 64 to 74% ; winter conditions - 74 to 83%. At first glance, it would appear that higher relative humidity gives poorer durability indexes. However, other work by Griesel (Griesel and Alexander (2001)), has shown that, in the range 60-80%, relative humidity plays a very minor role in influencing index values. On the other hand Griesel has shown that temperature in the range 18 to 35°C has a very profound influence on index values, with values generally improving up to about 28°C, whereafter they may deteriorate due to increased rates of evaporation from the surface concrete. Therefore, the results in Figure 7 are consistent with Griesel's observations, with temperature playing the dominant role in influencing the results. Despite the higher relative humidity pertaining at lower temperature, lower temperature has retarded the early hydration of the cement, leading to poorer index results. Conversely, higher temperature (up to about 22°C) facilitated more rapid hydration, and correspondingly better index results, despite the higher rate of evaporation from the concrete that would occur at these temperatures.

Figure 7: Average air temperature of the first 7 days after casting vs. index values of actual structures



4.4 Variability of index results

In order for the three durability index tests to be accepted as standard tests on construction sites, the degree of variability within a single set of test determinations needs to be obtained and shown not to be excessive. The data from the research done in this project are not sufficient to provide specific values for such a criterion. However, the 'single operator coefficients of variation' of the results are presented in Table 4 as a first step in obtaining limits for the variability of the durability indexes of site concrete.

In a previous study, Streicher (1996) determined the variability of the durability index tests conducted by two different operators on laboratory-made concrete. A 'single-operator coefficient of variation (1s%)' was calculated for each operator. A true single operator coefficient of variation as defined in ASTM C670-91a (1991) is an estimate of the variability of a large group of individual test results when the tests have been made on the same material by a single operator using the same apparatus in the same laboratory over a relatively short period of time. However, the values of 1s% that Streicher calculated were not determined from a large number of tests conducted on the same material and also not over a relatively short period of time. Instead, different types of concrete were used, each having its own degree of material variability, and the testing was conducted over several months. Sufficiently low variability was, however, obtained which gave a good indication that the index tests done by Streicher's two operators gave reliable results. Although the results are not true 1s% values, they give an indication of the variability that can be expected when the tests are conducted on different types of concrete over a period of time and are presented here for comparative purposes.

In work preliminary to this study, several sets of laboratory concretes ranging from 20 to 60 MPa, with CEM I, CEM I/CSF and CEM I/FA as binders, were tested and their 1s% values determined. These are also shown in Table 4.

Of all the concretes tested, the highest variability was obtained in the indexes of the actual structures. The variability of the chloride conductivity and oxygen permeability indexes of the actual structures was approximately double that of the wet-cured site concrete. This was probably due to variations in curing effectiveness and degree of compaction across the areas sampled. The variabilities of the water sorptivity indexes of the actual structures and wet-cured cubes were very similar, but approximately double those of the other wet-cured concretes tested. The variability of indexes for the ready-mixed concrete was low, and of the same order as indexes for the concrete made in the laboratory in this study and the concrete tested by Streicher's two operators (1996).

The variability of the water sorptivity and chloride conductivity results of the site concrete reduced as time progressed and the operator became more experienced with the test procedures. The high coefficient of variation determined on some of the sites corresponded with samples containing areas of honeycombing, cracks or bleed voids.

Table 4: Estimates of the single operator coefficients of variation (1s%)

Concrete source	Water sorptivity	Oxygen permeability	Chloride conductivity
Actual structures	13 %	3 %	14 %
Wet-cured, site mixed concrete	12 %	2 %	7 %
Wet-cured, ready mixed concrete	7 %	1 %	5 %
Laboratory	5 %	1 %	4 %
Streicher (1996) operator 1	8 %	2 %	8 %
Streicher (1996) operator 2	6 %	1 %	6 %

5 CONCLUSIONS

5.1 Durability indexes of the wet-cured cubes

a) Water sorptivity

The ready-mixed concrete results reveal that, other things being equal, cement type has a significant influence on the water sorptivity indexes of wet-cured concrete. The ready-mixed concrete results were very consistent for each cement type used, and this indicates good control of mixing and batching procedures at the ready-mixed plant. On the other hand, the site-mixed concrete results varied significantly and revealed that the characteristics of the materials in the mix, other than the cement, have a noticeable influence on the water sorptivity indexes of wet-cured cubes. Compressive strength did not have much effect on the wet-cured results.

b) Oxygen permeability

The oxygen permeability indexes of the wet-cured cubes of the various sites generally improved with increasing strength. However, the results also indicated the likelihood that the characteristics of the mix constituents (for example the grading and type of the aggregates) also have an effect. Because of the small number of sites used in this study and the large variety of different mix constituents, the particular influences could not be shown conclusively.

The results furthermore revealed that where the mix constituents are kept the same, the compressive strength has a marked influence on the oxygen permeability indexes of the wet-cured cubes. The ready-mix results indicate that cement type also plays an important role in achieving impermeable concrete. Higher strength LASRC concrete is more permeable than lower strength CEM I/CSF concrete.

c) Chloride conductivity

For low to medium strength concretes, the chloride conductivity indexes of the wet-cured cubes were sensitive to changes in the cement content and hence the compressive strength of the concrete. The results revealed that the chloride conductivity index is not as sensitive to mix constituents, other than cement type, as the other two tests.

5.2 Durability indexes of the actual structures

The durability indexes of the actual structures are generally inferior to the indexes of the wet-cured cubes. This indicates that casting, placing and curing practices on site generally result in concrete of lower quality than that of a 28 day wet-cured cube. Furthermore, the indexes of the actual structures contained more scatter than the indexes of the wet-cured cubes. This verifies that current site practices lead to concrete of which the quality is more variable than that of wet-cured cubes of the same mixes. It can be argued that this is due to the lower degree of control pertaining to on-site casting, placing and curing practices, and because of different construction methods used from site to site.

a) Water sorptivity

The surface quality of site concrete as reflected by the water sorptivity indexes was very dependent on the method of surface finish. In contrast to the wet-cured cubes, compressive strength had a noticeable effect.

b) Oxygen permeability

The influence of the mix constituents was smaller than in the case of the oxygen permeability indexes of the wet-cured cubes. It was considered that results from the actual structures were more dependent on site conditions such as efficiency of curing, the degree of compaction and the formation of cracks due to shrinkage. Poor correlation was found between the indexes of the wet-cured cubes and the actual structures, revealing that even with a good combination of high quality mix constituents, poor indexes can result for site concrete when the concrete is not adequately compacted and sufficiently cured.

c) Chloride conductivity

The chloride conductivity indexes of the actual structures contained less scatter than those of the other two tests, confirming the test's sensitivity to cement chemistry.

5.3 Environmental effects

The influence of the average air temperature in the first seven days after casting was dominant. Generally, higher temperature within the range 14 to 22 C resulted in improved indexes. This reflects the fact that at lower temperature, the rate of hydration of the cement at early ages is retarded. At higher temperature (within the range given), despite potentially higher rates of evaporation, the increased hydration rate results in better quality concrete.

5.4 Variability of the index results

The durability indexes of the concrete of the actual structures showed greater variability than 28 day wet-cured cubes, showing that site practices result in concrete, the quality of which varies more than that of wet-cured cubes of the same mix. This further strengthens the argument that higher variability is due to site practices and the lower degree of control possible on site.

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