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Effect of Controlled Environment Conditions on Durability Index Parameters of Portland Cement Concretes

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ABSTRACT: Environmental conditions such as temperature and relative humidity, influence the rate of evaporation of moisture from the concrete pore structure. They therefore, have a direct influence on the development of transport properties which are related to durability. Portland cement concretes of various grades were wet-cured for different periods of time and exposed to controlled environmental conditions.

The influence of temperature, relative humidity and wind speed on potential durability of the cover layer were assessed by means of durability index parameters related to the transport processes of oxygen permeability, water sorptivity and chloride conductivity. Temperature, in the range of 18°C to 35°C, had the most significant influence on the results. The effect of elevated temperatures on evaporation and hydration resulted in either significant reductions or improvements of potential durability.

The influence of relative humidity the range 50% to 65%, was less significant. Exposure to 82% relative humidity resulted in significant improvements in the indexes of poorly cured concretes, while well-cured concretes were insensitive to changes in relative humidity. The influence of wind speed on potential durability was insignificant.

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TECHNICAL PAPER

Mark G Alexander, Ph.D., and Eben J. Griesel won the The Sanford E. Thompson Award for their paper, "Effect of Controlled Environmental Conditions on Durability Index Parameters of Portland Cement Concretes". Alexander is professor of Civil Engineering at the University of Cape Town and Griesel is an analyst programmer at GenusSoft in Johannesburg.

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KEYWORDS: *temperature, relative humidity, wind speed, durability, curing, cement hydration, covercrete properties, drying processes.*

Cement hydration and the development of the durability related properties of concrete are very sensitive to the availability of sufficient pore water [Parrott, 1988]. It has been shown [Patel et al, 1988; Parrott, 1988] that the rate of cement hydration, compared to saturated conditions, drops to 50% at 90% pore relative humidity (PRH), and to 32% at 80% PRH, at 20°C.

As most of the medium to large capillaries (with pores larger than 20 nm) of the surface layers of concrete are emptied by evaporation above 90% PRH [Soroka, 1979], it follows that continued hydration will affect porosity changes only in the smaller capillaries. Together with the slower rates of hydration below pore saturation, significant improvements of durability related properties would therefore occur primarily at high pore relative humidities. Previous work indicated that the PRH threshold for significant porosity changes is 95% [Patel et al, 1988; Parrott, 1988].

The rate of moisture loss from the surface layers ("covercrete") of early age concrete will thus have an important influence on the degree to which the covercrete properties develop. It is reasonable to expect that, to a large extent, long-term durability

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performance of reinforced concrete will be related to early age drying processes. There are two sets of factors that influence the initial rate of moisture loss:

1. The inherent microstructure of the covercrete, influenced by aspects such as the water:binder ratio, binder type, initial period of wet curing and degree of compaction. Dense microstructures will result in more efficient retention of pore water, longer periods of continued hydration and thus better long-term durability performance.
2. The environmental conditions such as temperature, relative humidity and wind speed. These factors influence the rate of evaporation of pore water, while temperature also influences the rate of cement hydration. Elevated temperatures will therefore lead to both increased rates of hydration and evaporation, and the resulting covercrete microstructure will be a function of the competitive nature of these two processes.

The influence of the environment on drying processes from hardened concrete is the focus of this paper. Portland cement (PC) concretes were wet cured for various periods of time and exposed to controlled environmental conditions, in order to establish the influence of temperature, relative humidity and wind speed on concrete drying and the potential durability[1] of the covercrete.

The influence of exposure conditions on the properties of the covercrete

At the start of exposure to drying of young concretes, the microstructure properties are practically constant throughout the thickness of the covercrete (except the extreme surface skin), and are functions of factors such as the water:binder ratio, the binder type and the initial period of wet curing [Griesel, 1999]. As soon as pore water starts evaporating from the surface, the pore relative humidity decreases, resulting in slower rates of hydration, and in diffusion of moisture towards exposed surfaces. This "drying front" progresses deeper into the concrete with time, and results in differing periods of time of effective cement hydration at different concrete depths. Thus the resulting durability characteristics, governed by the microstructure properties, vary with depth into the concrete.

The environment has an effect on this process by influencing:

1. The rate of moisture loss
2. The rate of hydration

The first of these is affected by temperature, relative humidity and possibly wind speed. The second is affected by temperature, since the rate of hydration increases with increasing temperature of the material. (In this case it is assumed that environmental temperature governs the temperature of the covercrete material).

This twofold effect of temperature introduces the possibility that elevated temperatures could either enhance or retard the potential development of the covercrete properties. At higher temperatures, the pore water will evaporate at a more rapid rate from the surface layers of the covercrete, while the concrete at deeper regions will benefit from the more rapid rate of hydration. This will lead to steeper gradients of the covercrete properties with depth than would be the case at mild temperatures. If the effect of the faster rate of evaporation outweighs the influence of faster hydration rates, the covercrete quality will be impaired, and vice versa.

The results of this investigation help to provide information on the influence of the environment on concrete drying and the development of covercrete properties.

Experimental procedure

The experimental procedure is illustrated in Figure 1. PC concretes of grades 20, 40 and 60 MPa (w: c ratios of 0.84, 0.56 and 0.40 respectively) were wet cured for 1, 3 and 7 days before the start of exposure. The drying regimes are summarised in Table 1. For the investigation of the influence of temperature, the relative humidity was kept at 52.5 ± 1.5%, and the concretes were exposed to temperatures of 19, 28 and 35°C. For the investigation of the influence of relative humidity, the temperature was kept at 19 ± 1°C, and the concretes were exposed to relative humidities of 54%, 66% and 82%. The drying environments were created inside environmental chambers that allowed temperature control by a thermostatically controlled heater-fan, and humidity control by means of saturated salt solutions.

The investigation of wind speed comprised exposing two sets of samples of the same grade and amount of wet curing to the same environment in terms of temperature and relative humidity. One set was exposed to moving air from a fan for the entire drying period, and the other was placed in still air. This investigation was limited to a concrete of poor quality (20 MPa, wet cured for 1 day) and a concrete of reasonably good quality (40 MPa, wet cured for 7 days).

[1] In the context of this paper, the potential durability of concrete can be defined as the degree of resistance of the covercrete to the conduction of chlorides, permeation of oxygen and absorption of water, as indexed by tests developed at the Universities of Cape Town and the Witwatersrand. See Streicher and Alexander [1995, 1999], Ballim [1993], and Alexander and Magee [1999].

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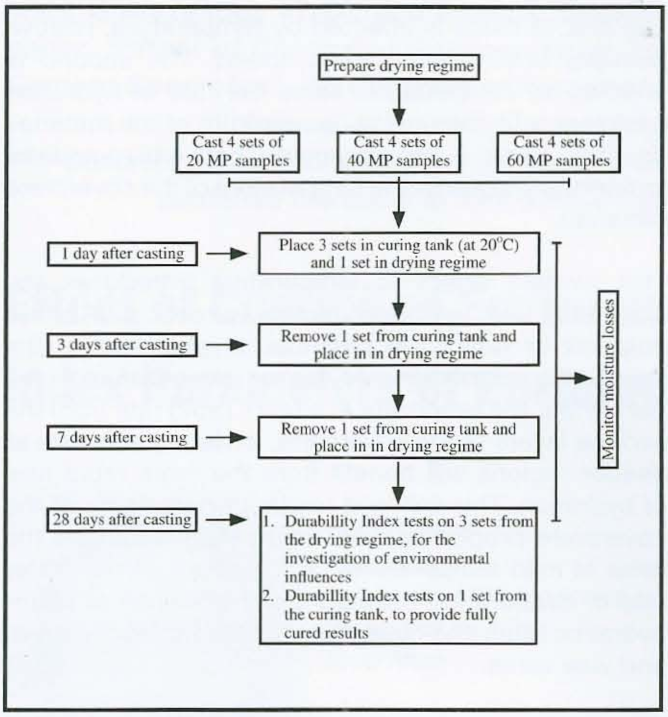

Figure 1: Experimental procedure

TABLE 1 - Summary of drying regimes

Temperature (°C) (± 1 °C)	Relative humidity (%) (± 1.5 %)	Wind speed (m/s)
19	54, 66 and 82	0.0
19, 28 and 35	52.5	0.0
20	60	5.6

The concretes were exposed to the controlled conditions until 28 days after casting. One set of samples was wet cured for the full 28 day period at 20°C, and provided fully cured results for each individual concrete batch. These were used for calibration of the results, and for the purpose of sensibly comparing the results from the different drying regimes[2].

Moisture losses were monitored during the drying period, and after 28 days the concretes were subjected to tests indexing their potential durability. These tests were recently developed at the Universities of Cape Town and the Witwatersrand, and will be reviewed briefly.

Durability index tests

The durability index tests involve measuring the chloride conductivity, water sorptivity and oxygen permeability of standard concrete samples [Alexander et al, 1999]. The concrete samples are cylindrical cores of 68 mm diameter and 25 mm thickness, drilled from the surface of concrete specimens, typically cubes. These samples are oven dried at 50°C and 15% RH prior to testing, until the change in mass is less than 0.1% over a 24 hour period [Alexander and Magee, 1999].

Water sorptivity index test

Sorptivity can be defined as the rate of movement of a water front through a porous material under capillary action [Alexander and Magee, 1999]. Pre-conditioned concrete samples are placed onto saturated layers of absorbent material in a plastic tray, and their mass gain monitored at prescribed time intervals. The sides of the samples are sealed prior to testing, to ensure uniaxial absorption. The water sorptivity index is calculated using the dimensions of the specimen, its porosity[3] and the absorption rate, and is interpreted as the rate of penetration of the water front, in mm/√h. The typical range of results (for fully cured PC concretes) is 8.5 mm/√h or less (for good quality concretes) to 15 mm/√h or more (for poor quality concretes).

Oxygen permeability index test

This test involves determining the rate at which oxygen permeates through a pre-conditioned concrete sample, using a falling head permeameter [Alexander and Magee, 1999]. An initial oxygen pressure differential of approximately 100 kPa is applied across the sample. The pressure decay with time is measured, and the Darcy coefficient of permeability is determined. The oxygen permeability index is the negative logarithm of the coefficient of permeability. The typical range of results for this index is from 10.5 (for good quality concretes) to 9.0 (for poor quality concretes), on a log scale.

Chloride conductivity index test

This test determines the conductivity of concrete samples, from their dimensions and electrical resistance. The samples are saturated with a 5 M NaCl solution prior to testing, by immersion under vacuum (-80 kPa) for 24 hours. The test procedure involves applying a potential of 10 V across the ends of the specimen and measuring the electrical current (DC) passing through, using a conduction cell filled with 5 M NaCl solution. The typical range of results for this test (for fully cured PC concretes) is from 1.0 mS/cm or less (for good quality concretes) to 3.5 mS/cm or more (for poor quality concretes).

Materials and mix proportions

The cement used was type CEM I-42.5 (equivalent to ASTM Type I), with a chemical composition as indicated in Table 2. The aggregates were 19 mm greywacke crushed stone and a pit sand of F.M. = 1.99. The concrete mix proportions are given in Table 3.

[2] A different concrete batch (of each grade) was used for the investigation of each of the drying regimes. The slight variation in concrete quality called for normalising of the results obtained. This was done by dividing the results from each drying regime by the fully cured results of the same investigation. The results discussed subsequently are these normalised results, multiplied by the average of the fully cured results from all the drying regimes investigated (see Table 4).

[3] The porosity is determined by vacuum saturation of the samples in a $Ca(OH)_2$ water solution after testing, and is equal to (saturated mass – dry mass).

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TABLE 2 - Oxide and clinker analyses of the cement

Chemical constituent	Percentage
CaO	65.7
SiO_2	22.1
Al_2O_3	3.9
Fe_2O_3	4.3
Mn_2O_3	0.12
TiO_2	0.19
MgO	0.71
P_2O_5	0.14
SO_3	2.1
K_2O	0.51
Na_2O	0.19
Clinker component	**Percentage**
C_3S	59.9
C_2S	18.4
C_3A	3.3
C_4AF	13.1
Loss on ignition (%)	2.2
Blaine surface area (cm^2/g)	2900

TABLE 3 - Concrete mix proportions

	Mix proportions per m^3		
	20 MPa	40 MPa	60 MPa
w:c	0.84	0.56	0.40
Water (kg)	180	185	195
Cement (kg)	214	330	488
Stone (kg)	1050	1050	1050
Sand (kg)	942	831	672

Results and discussion

Results of wet cured concrete specimens

The mean index values from fully cured concrete (wet cured at 20°C for 28 days) are given in Table 4, together with the mean of the 28 day compressive strengths. This is a good illustration of the typical performance of PC concretes, varying from poor quality to reasonably good quality. The indexes obtained from the 60 MPa concretes approached an upper limit of what might be expected, while the indexes of the 20 MPa concretes represent a lower limit, for well-cured PC concretes. For poorly cured concretes a much larger range of index values can be expected, as will be seen in the subsequent discussion.

TABLE 4 - Compressive strength and durability index test results for 28 day wet-cured concretes (at 20°C)

Property	Concrete grade		
	20 MPa	40 MPa	60 MPa
28 day compressive strength (MPa)	18.3	38.9	57.2
Water sorptivity index (mm/√h)	10.8	8.7	8.5
Oxygen permeability index	9.38	10.07	10.33
Chloride conductivity index (mS/cm)	2.57	1.77	1.17

The influence of temperature on the durability indexes of drying concretes

The expectation that environmental temperature could significantly influence the potential durability of concrete was confirmed with the results obtained during this investigation. The results for the 20 MPa concretes can be used as a typical illustration of the general trends (Figure 2).

Concretes wet cured for 1 day performed poorly at a temperature of 35°C, while results obtained from well cured concretes were generally similar to, or better than those obtained at 19°C (and 20°C). This indicated that sufficient wet curing (7 days) ensured that the covercrete had a sufficiently dense microstructure, enabling it to retain its moisture and benefit from the more rapid rates of hydration at 35°C.

The temperature of 28°C appeared to be close to an optimum, in providing rapid hydration rates without excessively depriving the covercrete of its moisture. Most of the indexes obtained from this drying regime were better than results from the other exposure temperatures, irrespective of the period of wet curing.

A difference in trend was observed for the water sorptivity index, compared to the other indexes. Since this index is more sensitive to the properties of the extreme outer layers of the covercrete, exposure to a temperature of 35°C

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resulted in significant increases of this index (i.e. poorer quality). This was especially noted for poorly cured concretes, and the trend persisted for medium and well cured concretes.

The general trends observed for the 20 MPa concretes were also true for the better quality concretes (40 and 60 MPa) - see Figure 2. The trends observed for the 60 MPa concretes were almost identical to those of the 40 MPa concretes, with slightly better index values. However, one significant exception was that the oxygen permeability indexes obtained after exposure to 35°C were significantly poorer than those obtained from the other two drying regimes. This could have been a result of thermal shock when the samples were moved directly from the curing tank (at 20°C) to the drying regime, or due to micro-cracking at this elevated temperature. An explanation is that the 40 and 60 MPa concretes had a significantly denser microstructure than the 20 MPa concretes, and were thus more likely to produce internal stresses leading to micro-cracking during thermal expansion and rapid volumetric changes.

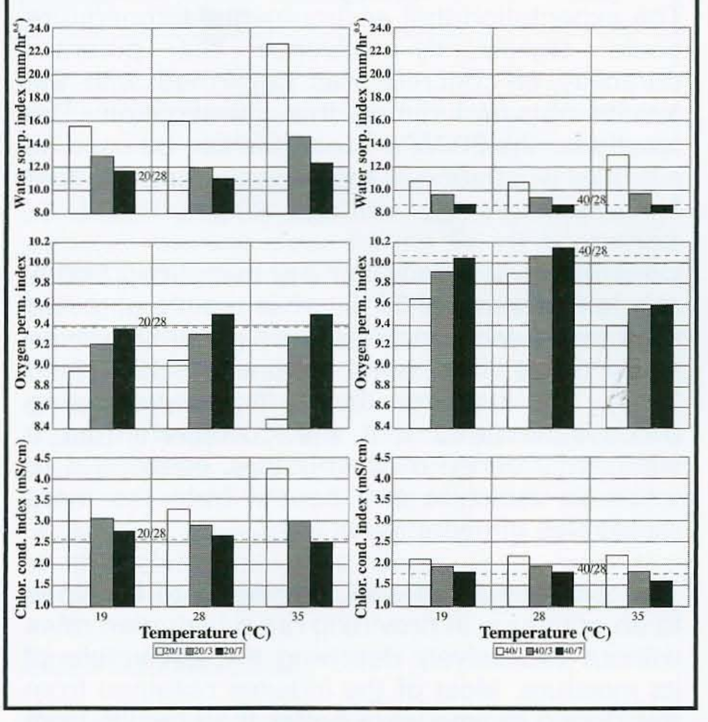

Figure 2: The influence of temperature on the durability indexes of 20 and 40 MPa concretes (at a relative humidity of approximately 50%). An abbreviation 20/1 indicates a 20 MPa concrete wet cured for 1 day before exposing it to the appropriate environment. Unlike the other two durability indexes, a higher value of the oxygen permeability index indicates better quality. Also shown on the figure are the 28 day, 20°C wet-cured benchmark values, for comparison.

The influence of relative humidity on the durability indexes of drying concretes

Variations in relative humidity had a much smaller influence on the durability indexes of the concretes investigated. The trends observed were similar for all three concrete grades. The results of the 40 MPa concretes are shown in Figure 3 by way of illustration.

In general, results were very similar for exposure at 54% and 66% relative humidity. An important observation that can be made from this investigation is that the durability indexes of poorly cured concretes improved significantly when exposed to 82% RH, while well-cured concretes were insensitive to changes in relative humidity. This was most evident for the water sorptivity index, and indicates that relative humidities above 80% provide, to some extent, additional curing for concrete structures.

The influence of wind speed on the durability indexes of drying concretes

The index results obtained from the wind speed investigations are given in Table 5. For both the 20/1 and 40/7 samples, the indexes were slightly better for the samples drying in still air. However, if the general variability of results is taken into consideration, the conclusion can be made that the influence of wind speed is minor, and negligible for practical purposes.

This can be explained by considering that wind only affects the rate of evaporation from the surface of the hardened concrete. Thus wind should only have an effect on moisture loss for as long as pore water is located in capillaries open to the surrounding environment. This would be the case in concretes with w:c ratios higher than 0.70 and/or poorly cured concretes, with large degrees of interconnection of capillaries [Verbeck, 1978].

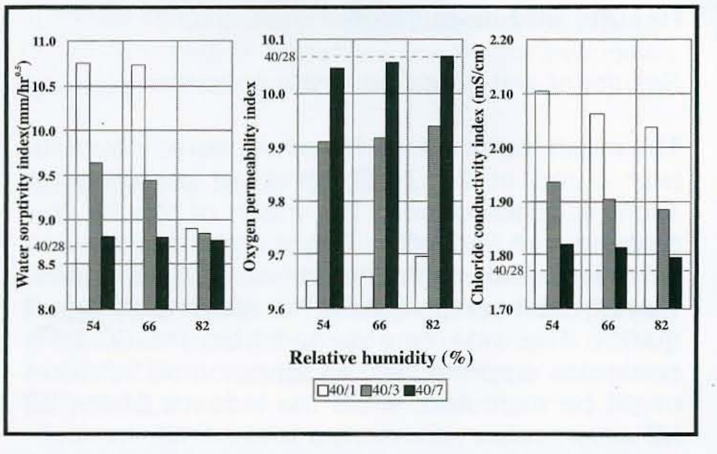

Figure 3: The influence of relative humidity on the durability indexes of 40 MPa concretes (19°C)

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TABLE 5 - Index results of the wind speed investigations (mean wind speed = 5.6 m/s)

Index test	Concrete grade and curing			
	20/1		40/7	
	Wind	Still air	Wind	Still air
Water sorptivity index (mm/√h)	22.9	21.4	8.9	8.9
Oxygen permeability index	8.5	8.7	10.0	10.1
Chloride conductivity index (mS/cm)	3.8	3.4	2.3	2.1

General discussion

Drying processes in hardened concrete influence the pore moisture distribution of the covercrete, and therefore play an important role in the development of durability-related properties. The rate of moisture loss depends firstly on the inherent microstructure of the covercrete, which is a function of factors such as the w:c ratio and the initial curing history. Well-cured concretes possess dense microstructures, and therefore have the ability to retain their moisture for longer periods of time, thus enhancing hydration. Poorly cured concretes, on the other hand, have an open pore structure and lose their moisture rapidly due to drying, resulting in poorer durability performance.

It was seen in this study that the environment significantly influences the potential durability of PC concretes, as measured by the index tests. Temperature had a twofold effect, in that it influenced both the rate of evaporation and the rate of cement hydration. These two effects are in competition, and elevated temperatures could either improve or impair the potential durability of concrete. The importance of proper curing was once again accentuated, especially for the lower concrete grades and elevated temperatures.

Relative humidity influences the rate of evaporation, and therefore the loss of pore moisture. Above 80% RH, the rate of evaporation slows significantly and results in good durability performance. Although hot, humid environments were not investigated, the results indicate that such conditions could be very beneficial for the development of durability-related properties.

Wind speed played a minor role in the rate of moisture loss and the resulting potential durability of concretes of poor quality, while well-cured concretes with a lower w:c ratio seemed to be unaffected. This indicates that wind plays a role in moisture loss for as long as the capillary pores of the covercrete are interconnected, and becomes insignificant as soon as the capillary porosity de-percolates (becomes isolated).

Ultimately the findings of this investigation emphasize the sensitivity of concrete durability to various factors during the initial phases of construction. The indication is that the potential service life of reinforced concrete structures made with PC is established within the first few weeks after casting, and could be significantly increased if the influence of the environment is understood and taken into consideration. For binder types other than PC, such as slag and fly ash blends, it is likely that a longer period will be required to develop the durability properties, implying that additional care is needed to protect the concrete from adverse early drying conditions [Mackechnie and Alexander, 2000].

Summary

Portland Cement (PC) concretes of grades 20, 40 and 60 MPa were wet cured for 1, 3 and 7 days and exposed to controlled environmental conditions, in terms of temperature, relative humidity and wind speed. Temperatures investigated were 19°C, 28°C and 35°C, at a relative humidity of 52.5 ± 1.5%. The investigation of relative humidity included conditions of 54%, 66% and 82% RH, at a temperature of 19 ± 1°C. The influence of wind speed was assessed by comparing results of samples exposed to a wind speed of 5.6 m/s to results of samples drying in still air.

The influence of the environment on the development of covercrete properties was assessed by means of three durability index parameters, which provide a measure of the transport processes related to oxygen permeability, chloride conductivity and water sorptivity.

As a result of its influence on both the rate of evaporation and the rate of hydration, temperature had a significant effect on the durability indexes of PC concretes, as measured by the chosen tests. Inadequately cured concretes lost their moisture rapidly at a temperature of 35°C and performed very poorly, while well-cured concretes seemed to benefit from the accelerated rates of hydration. The oxygen permeability indexes of

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the 40 and 60 MPa concretes were impaired at this temperature, possibly due to internal stresses leading to micro-cracking during thermal expansion and rapid volumetric changes. At 28°C the effects of temperature were well balanced, and exposure to this temperature resulted in consistently good covercrete performance (relative to the other two drying temperatures).

The influence of relative humidity was much less significant, and exposure to 54% and 66% relative humidity resulted in similar durability indexes. Exposure to 82% relative humidity resulted in significant improvements in the indexes of poorly cured concretes, while well-cured concretes were insensitive to changes in relative humidity.

The influence of wind speed on concrete drying and potential durability was insignificant in practical terms for both poor and good quality concretes.

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