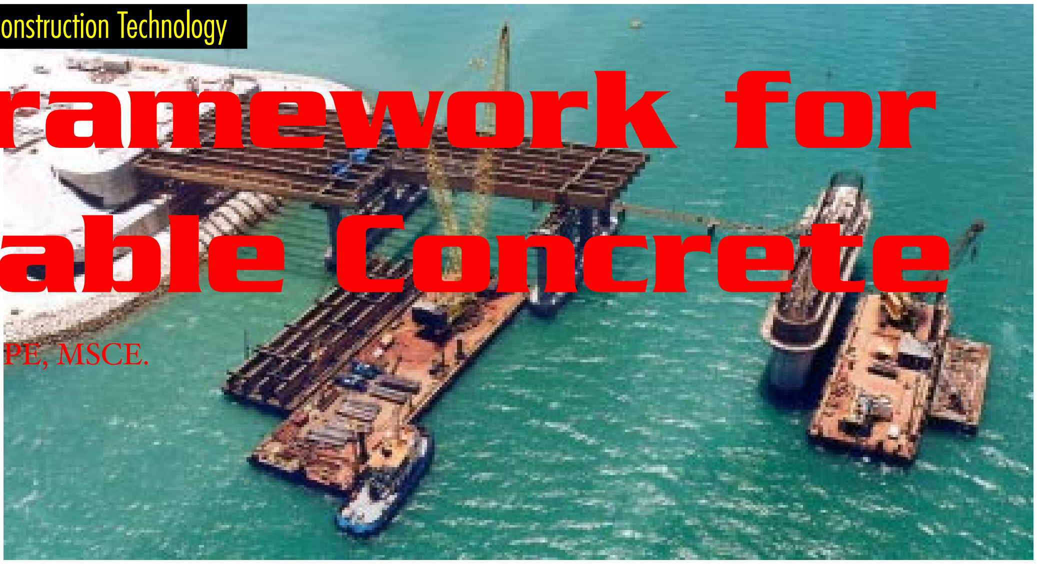
In the last 5 years, multiple industrial, commercial and infrastructure projects in hot and temperate climates of up to US$ 2.5 billion have embraced a new technical approach to concrete durability. This new approach represents a radical departure from more traditional concrete technologies. Key elements are presented in this presentation, along with the performance results of the most recent and largest project to use these concepts to date, the Shaikh Khalifa Bin Salman Deep Water Port in Bahrain (known as the Port) of the Arabian Gulf region.

Advances in Concrete Construction Technology

A Framework for Durable Concrete

By G. R. Summers, PE, MSCE.

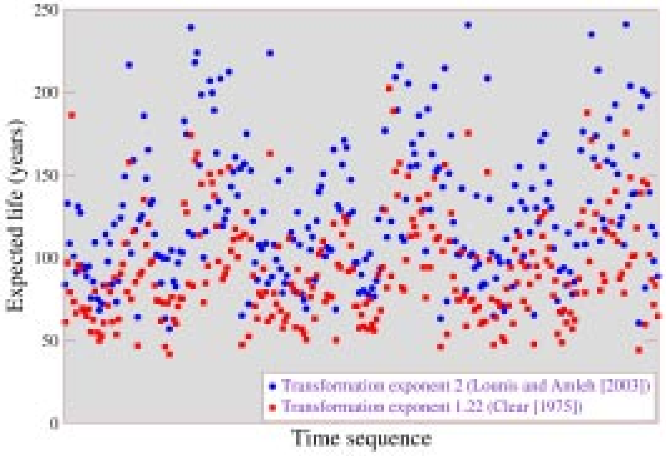


A marine bridge under construction in Bahrain. Concrete elements at this stage were cast using normal practices and were virtually crack-free. Photo courtesy the Ministry of Works and Housing, Bahrain, 2002.

Many international concrete experts have concluded that the Arabian Gulf region has one of the most aggressive marine climates in the world for reinforced concrete. No point in Bahrain is more than 3 km from the sea, seawater salinity values are 50 percent higher than the world average (approaching 45,000 ppm), with globally extreme air and sea temperatures, globally extreme solar radiation conditions and carbonation rates that are four times higher than those in London [2, 3].

Faced with such costly circumstances, the Ministry of Works and Housing of Bahrain launched a series of research projects. These natural exposure studies, jointly carried out with leading European research agencies, have spanned more than 20 years. Most of the traditional indicators of durability such as cement type and amount, cover depth, degree of curing, effect of contaminants, strength effects, reinforcing steel type (such as ferritic and austenitic stainless steels), reinforcing steel coatings (such as a range of epoxy materials and processes and others) were investigated.

Most recently, an exploratory and developmental phase was initiated during the 1990's that addressed concrete mixture and construction process optimisations. These programs examined the chemical activation energy of various cementitious mixtures and concrete mixtures, the influence of water in the mixture, associated early-age and longer-term volumetric distortion characteristics and in-situ durability assessment methods.



Result of EMR durability testing at the Port with cover transformation applied. The target lifespan of the structure is a minimum of 50 years, maintenance free, with a virtually unlimited design life. The chart represents a summary of 557 sets of EMR data. Plotted from tests carried out in 2003 [1].

OBJECTIVES OF PROJECT DURABILITY

Concrete must first be considered in the context of project durability [5], rather than just concrete durability. The objectives of project durability are to:

1. Minimise or eliminate construction process cracks due to shrinkage, thermal distress and other sources of volumetric distortion.

2. Minimise or eliminate the occurrence and distribution of load-induced (structural) cracks at the vicinity of severe exposure concrete elements in aggressive environmental conditions.

3. Enhance constructibility whereby concrete is to be placed and consolidated by normal methods without detrimental effect on construction schedules.

4. Produce a non-sorptive matrix from the perspective of in-situ testing and long-term performance.

5. Provide an economic solution for the given design and service life requirement.

Concrete mixtures that fit within the above criteria must, in a relative sense, have low heat development profiles, low shrinkage and creep characteristics, normal strength development and a non-sorptive matrix.

FRAMEWORK FOR DURABLE CONCRETE

To achieve project durability, it follows that concrete should be considered within the context of a framework, which can be identified as the Framework for Durable Concrete [6] which is as follows:

1. Optimise the mortar fraction, and then reduce the amount of it.

2. Limit water content to the lowest practical value.

3. Use cementitious materials that result in a concrete of low heat profile, but that allow the concrete mixture to have normal strength gain characteristics.

4. Develop the mixtures, design geometries and degree of reinforcement to reduce or eliminate the risk of crack development from any and all causes.

5. Monitor the in-situ performance of the structure.

The application of these principles has led to the development of the following new technical concepts:

Mobility of the mortar fraction [5, 6]. This is related to the mobility of mortar at low water contents. The cementitious material is the key, because it can be manufactured, classified or blended to produce optimal mobility for a given water content, sand and stone. Another innovation is the use of a highly reactive super fine pozzolan. The use of a small quantity of this type of engineered mineral, in the region of 5 to 10 percent by weight of cementitious material, can lead to a highly mobile mortar of reduced water

Concrete works at the Port in Bahrain during 2003. Concrete work of the 2.4 km Quay Wall was completed ahead of schedule, with virtually crack-free concrete elements. Photo courtesy of Posford Haskoning Consultants (UK/ Bahrain).

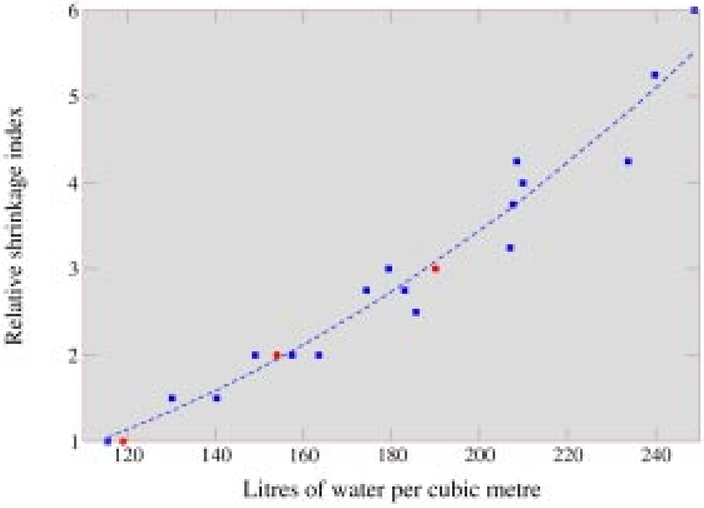
A typical EMR specimen from the Port. Note the tight spacing of the coarse aggregate. Even with 51% coarse aggregate by volume (most concrete today falls within the range of 38 to 44%), these mixtures provided highly cohesive concrete with slump values generally more than 10 cm, that were pumped, conveyed or bucketed into position. Photo courtesy of the University of Wales, Swansea; EMR specimen provided by Delmon Ready Mixed Concrete Products of Bahrain.

demand and enhanced strength.

Relative shrinkage potential [5, 6]. The concept of relative shrinkage potential allows one to quantify the advantages of reduced water content. Thus a reduction of water from 160 litres to 125 litres per cubic metre of concrete can lead to a 50 percent reduction in relative shrinkage potential for a given source of coarse aggregate.

Relative life extension [5, 6]. The concept of relative life extension is based on the application of non-steady state capillary theory to life prediction, for realistic and rational assessment purposes. From capillary theory, the author can prove that reducing the capillary index (I) will extend the lifespan (t) of the concrete, not by a factor of 2, but by the power of 2, according to the following formula:

$$t_2 = t_1 \left(\frac{I_1}{I_2}\right)^2$$

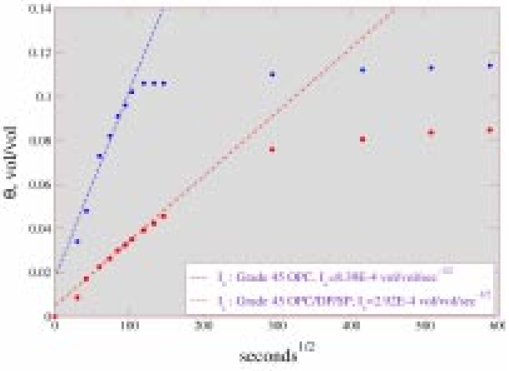


The new concept of relative shrinkage potential developed and introduced by the author

Statistical assessment and inspection of the capillary index confirms that it is a robust and repeatable parameter. This contrasts sharply with alternatives such as the diffusivity coefficient which is often referred to in 'effective' terms due to uncertainty and error in its measurement or application[7].

In-situ, environmentally matched replicate (emr) testing [5, 8]. Construction monitoring of durability performance is based on a new test method, the 30:180 Durability Test[9, 10], used on emr specimens (i.e. specimens cured in the same manner as the structure). In addition to durability testing, strength testing of emr samples is also used to assess the effectiveness of curing practices. For the first time, the practical quality assessment of the durability and strength of in-situ concrete is possible, which also more clearly defines the contractual 'grey area' of responsibility between the concrete producer and concrete contractor.

One of the key tenets of this approach is the acceptance of capillary theory as the governing mechanism of chloride ingress. This is justified by understanding the common misconceptions and truths surrounding alternative deterioration theories and test methods.



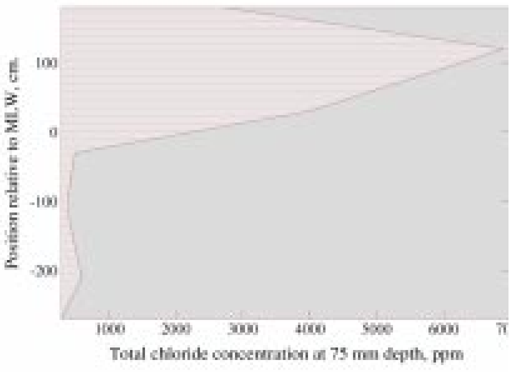
From the 30:180 Durability Test [9, 10], a direct comparison of the Capillary Index, or Ic, can be used to predict the relative life extension of the subject concrete mixture. This result is from tests of samples of concrete associated with the Port.

CHLORIDE INGRESS THEORIES

Chloride ingress theories govern the basis of concrete durability design and implementation. For this reason it is vital to review the three major concepts, the diffusion theory, permeability and capillary behaviour, to briefly review test methods used and confirm why capillary theory is the superior approach.

Diffusion Theory

Diffusion theory is based entirely on the movement of ions through a liquid. Many leading researchers hold the view that diffusion governs durability processes. The reality is that the diffusion equation is an artificial simulation that is not a realistic predictor of chloride intrusion. Concrete designed to meet diffusion criteria often leads to detrimental side effects during construction that include excessive heat, excessive shrinkage and cracking problems. Paradoxically, the conditions of the assumptions behind the diffusion theory (complete saturation of the concrete in service) lead to a non-aggressive environment in practice. This is illustrated in the figure below which is taken from studies done of chloride profiles along the walls of a marine intake structure in Florida, a structure that was 15 years in service.



Chloride profiles along the wall of a marine intake structure in Florida, relative to the mean low water line (mlw). Baseline chloride concentration is 300 ppm.

The portion of this structure that would be subjected to diffusion conditions is the zone below the 0 level, as this is the 'saturated' zone in service. However, it is absolutely clear that the chloride level is relatively insignificant when compared to the spray and splash zone (above the 0 position).

The region above zero is governed by wetting and drying behaviour; or the intermittent absorption and desorption of the concrete. This is the zone of capillary influence, and it is clear that chloride penetration is comparatively fast within this zone.

Rapid (accelerated) measurement of diffusion has been attempted. Commonly used methods include AASHTO T 277 or ASTM C 1202 that have been widely used in specifications since the early 1990's. These are included herein as indirect tests of chloride diffusion. However, this RCP, or Rapid Chloride Permeability approach has proved to be fallible for different mixture compositions, and leading practitioners throughout the world have questioned the use of this method as "numerous concrete projects in the past with specified coulombs of 600 to 1000 have created job-site construction problems and cracking"[11]. Accordingly, many leading experts now consider the RCP test to be inadequate for durability testing and for generalised specification {11, 12, 13, 14], with one concluding that the test is just a "numbers game" [14].

Permeability Theory

Permeability theory is based on fluid flow. The driving force for the flow is a pressure differential, often referred to as pressure head. The basic theory is attributed to Darcy. Although permeability theory does have merits with regards to chloride ingress behaviour, the reality is that theoretical permeability conditions (complete saturation and significant hydraulic pressure head) rarely occur in practice. When they do, like diffusion, they often result in a non-aggressive environment in service. In reality, the hazardous zone in concrete subjected to permeation, such as a concrete dam, is not the saturated zone, but the zone of capillary rise immediately above the saturated zone, again, capillary action governs here.

Permeability is perhaps applicable to concrete dam structures or other water retaining and restraining structures that are exposed to hydraulic gradients (differences in levels of water across the section of interest). This form of permeability can move chlorides into the concrete but the service conditions that are required to cause water movement are infrequent. Furthermore, under so-called 'saturated' conditions, the sample will still contain entrapped air of some quantity and this negates the validity and strict application of the

Darcy theory.

One popular indirect test of Darcy's permeability theory is the DIN 1048 water penetration test. In this test a sample of concrete is placed in a chamber containing water and pressurised at up to 7-bars. The final outcome is a water penetration value, in millimetres, that often is specified to be less than 5. This test has nothing to do with capillary sorption or diffusion, but is more in line with Darcy's Law, or the flow of a fluid through a pipe under pressure, as such the practical applicability of the test is limited.

Capillary Theory

Practical experience, observation and field testing all confirm that capillary theory is the key to durability. The reality is that the conditions of capillary sorption and suction are in fact the definition of aggressive environments (i. e. partially saturated concrete and wetting and drying conditions). Long-term observation in aggressive environments confirms this theory, as previously noted in Fig 7.

Equilibrium Sorption. In the real world, the coefficient of permeability is a function of the volumetric moisture content, as represented by the symbol q. Capillary suction, or ho, is also linked to the volumetric moisture content, qo. These suction forces were quantified for the first time by Savage and Janssen [15] on a concrete mixture with a w/c ratio of 0.40 (see Table 1). Remarkably, they found that suction forces in dry concrete can reach 2,000,000 m of pressure head.

Table 1. Capillary Suction Values[15].

θ_o, %	$h_o(\theta)$, m
11	200
10	2,000
8	4,500
6	10,000
4	20,000
2	70,000
1	2,000,000

Although the theoretical derivation of the capillary absorption equations is beyond the scope of this article, the following simplified relationships [5, 6} can be derived:

$$h_0 = M_0 \frac{\cos\alpha}{\phi} \text{ for } M_0 = \frac{4\sigma}{\rho g}$$

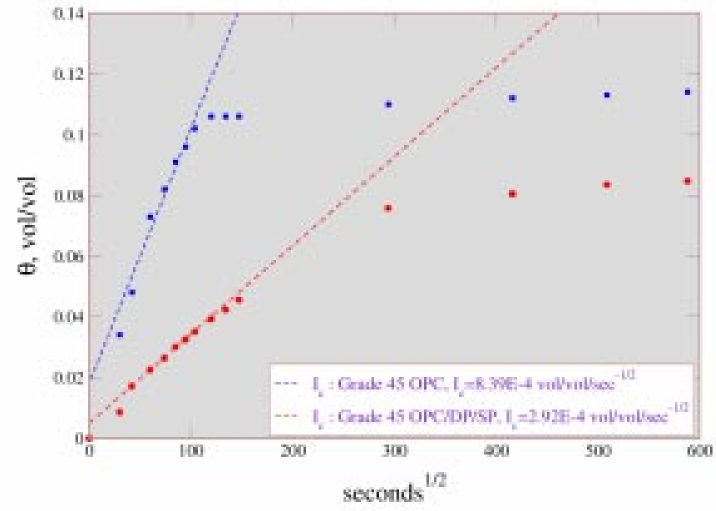
Where: h_0 = steady state suction pressure.
α = meniscus angle.
ϕ = diameter of tube.
σ = surface tension of liquid.
ρ = density of liquid.
g = gravitational acceleration constant.

The importance of the above equation is that the suction pressure is proportional to the ratio of the meniscus angle (alpha) to the diameter of the continuous pores, (phi). The proportionality constant, or Mo, is dependent on the properties of the fluid and other constants. Therefore, capillary theory incorporates the materials parameters and the interaction of the liquid and pores (defined by the meniscus angle). This goes far beyond either of the other theories and further illustrates just how powerful the approach can be for developing durable concrete.

Non-Equilibrium Sorption. Another major advantage of capillary theory is the ability to measure the non-equilibrium condition, or Capillary Index [6, 8]; which is the initial slope of the relationship between time and absorbed liquid. This is the most important property of the concrete because it determines the affinity for rapid uptake of moisture and the rapid uptake of chloride. The lower the rate of moisture uptake, the more durable the concrete, as less chloride will accumulate over time[5].

Other than the 30:180 Durability Test [9, 10], there does not seem to be any robust and repeatable method that currently measures this non-equilibrium characteristic of the concrete.

Although the detailed review of the test method is beyond the scope of this article, it is a simple procedure that does not require specialised equipment and can easily be integrated into the routine quality control assessment programs as was done at the Port.



Result of the 30:180 Durability Test [9, 10] on specimens associated with the Port project. The initial slope of each curve is the non-equilibrium portion, and the capillary index is this slope.

CASE STUDY: A DEEP WATER PORT, BAHRAIN

To illustrate the effectiveness of this approach, performance data from a major deep-water port project is presented. The Shaikh Khalifa Bin Salman Deep Water Port in Bahrain is perhaps the largest and most ambitious pure civil engineering work ever undertaken there. The project consists of the construction of a new peninsula that is bounded by a 7.2 km rock bund on the seaward side, and a 2.4 km concrete quay wall on the harbour side. The US$ 500 million project utilises a total of 350,000 cu m of concrete and some 25 million tonnes of stone and sand. The project is scheduled for completion in late 2004, but the concrete works are essentially completed.

Specifications and criteria

This section is provided to identify some of the unique features of the specification. A snapshot of key concrete specification features is provided in Table 2. These follow the Frameworks principles. This approach is a radical departure from the normal specification practice. Note that:

1. There is no minimum binder content, only a maximum.
2. Halide content, as opposed to only chloride content, is specified. Halides include the halogen salts, primarily bromide, chloride, iodide and fluoride (astatide is also there, but is so rare in nature that it is not included). Each of these is aggressive to steel in concrete.
3. There is a minimum coarse aggregate by volume, which effectively controls the mortar fraction, shrinkage and creep.
4. A maximum free water content is specified to control shrinkage potential and to reduce the rate of heat transmission by reducing the specific heat of the mixture.
5. The capillary index value (from the 30:180 Durability Test) is specified as a maximum for verification trials and for production concrete based on a moving average. These tests are conducted on emr specimens.
6. The permeable pore space according to ASTM C642 is used is a mixture optimisation criteria.
7. The binder consists of a three-part mixture that is 70 percent Portland cement, 30 percent classified fly ash conforming to BS 3892 plus the addition of either a highly reactive manufactured pozzolan (super fine pozzolan or sfp) or silica fume.

Table 2 : Specification of Severe Exposure Concrete [1]

Property	Limits
Maximum binder content, kg/cu m	400
Target pozzolan content, % by mass of binder	30
Additions to binder, minimum/maximum, %	sfp 5/10
super fine pozzolan (sfp) or silica fume (sf)	sf 5/7
Maximum w/c by mass	0.37
Maximum halide, kg/cu m	0.70
Minimum coarse aggregate by volume, %	50
Maximum free water, l/cu m	125
Capillary index, Ic, v/v/sec 1/2 x 10-4, Vmax/Qmax	3.5/4.5
Maximum permeable pore space, %	7

Materials and mixtures

Table 3 contains the typical yield-adjusted mixture designs and the verification trial test results for the severe exposure mixtures. There were two different batch plants used for the project, a British Steelfields plant and a German Stetter plant. Both plants were used to produce severe exposure concrete mixtures. Initially there were some differences in efficiency that were detected by the testing regime. Interestingly, the 30:180 Durability Test [1, 5, 6] detected this difference in mixing efficiency and led to a means of monitoring the consistency of the batching process.

The data for the permeable pore space and capillary index is based on the result of tests of samples cured with the structure (emr specimens). The exceptional performance of the strength of in-situ replicates at 7 days age is a key durability predictor and serves to refute the commonly held misconception that pozzolanic mixtures require more time for curing than ordinary Portland cement mixtures.

Table 3. Typical Mixture Trials Yield Adjusted/SSD Basis [1]

	HS36S6	HS36D6
Plant	Stetter	Steelfield
Portland cement (SRC), kg/m^3	249	254
Durapozz, kg/cu m	107	109
Superpozz, kg/cu m	18	18
Water, l/cu m	109	111
20 mm Stone, kg/cu m	770	781
10 mm Stone, kg/cu m	642	639
Sand, kg/cu m^3	624	601
Fibres (MBT Rheofibre_), kg/cu m	0.4	0.4
Admixture (MBT Rheo 855_), l/cu m	3.75	3
Slump, initial, mm	120	75
Fresh Density, kg/cu m^3	2519	2513
Temperature, Initial, C	28.4	32.2
Temperature, Max Rise, C	21.2	21.9
Temperature, Max, C	49.6	54.1
Temperature, Max Delta, C	9.2	14.5
Permeable Pore Space, 7d, %	6.4	6.0 - 6.4
Capillary Index, vol/vol/sec$^{1/2}$ x 10^{-4}	2.6	2.7
7d Cube Strength, Lab, MPa	56.2	46.3
7d Cube Strength, In-situ, MPa	63.7	62.5
28d Cube Strength, Lab, MPa	73.7	59.2

Table 4 contains the results of fresh concrete properties. The specified slump was 50 mm minimum, and the results comply with this requirement. Considering that mixtures contain fibres, these slumps indicate a high workability. All other aspects are in compliance with the specification. Non-fibre mixtures had slumps generally in excess of 100 mm.

Table 4 : Field Monitoring Results to April 23, 2003 [1]

	Max	Min	Ave
Slump, mm	130	80	100
Plastic Density, kg/m^3	2550	2460	2510
Ambient Temp, C	31.7	21.2	25.9
Initial Concrete Temp, C	30.8	14.9	24.1

Table 5 provides a summary of the strength results. All results met the minimum strength requirement of 45 Mpa. Extensive testing of the strength of emr specimens was required, and these ranged from 42.5 to 77.0 Mpa at 7-days age.

Table 5 : Strength to April 29, 2003, MPa [1]

	Max	Min	Ave
7 day Laboratory	72.0	39.5	53.0
28 day Laboratory	91.0	58.0	72.4
7 day In-Situ (emr)	77.0	42.5	58.0

The capillary index results are presented in Table 6. As can be seen, the overall average for the project is right on target. The specification required that production concrete not exceed 4.5 x 10-4 vol/vol/sec 1/2. There are no absolute maximum or minimum limits specified for the project; this is addressed indirectly by the limit on the moving average result.

Table 6 : Capillary Index Results, 2003, 10^4 vol/vol/sec$^{1/2}$ [1]

	Max	Min	Ave
Individual Values	6.4	3.0	4.4
Moving Average of 10	5.2	3.5	4.4

Statistical life prediction

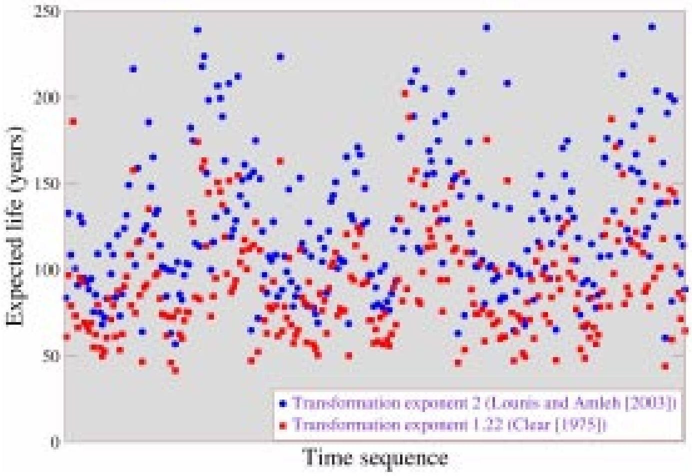
A statistical analysis of the data has been carried out using n=557 emr sets (each set being two to three cube specimens) accumulated between the period of October 2002 and April 2003. The analysis confirms three things:

1. The distribution of data approaches that of a normally distributed population density function,
2. The data is without time effects
3. Within-test error is not correlated to Ic.

Statistical simulation techniques were used to evaluate the appropriate close fit relationship for the capillary index (Ic) test data. The following probability relationship was developed for the Port {1, 9}:

$$f\,(Ic) = 0.25e^{-[(Ic-4.35)^2/1.29]}$$

For : $\overline{I_c} \geq 3.0$ *and* $I_c \geq 0$
Where : I_c *= Capillary Index, as vol/vol/sec*$^{1/2}$ *X 10*^{4}*, according to the 30:180 Durability Test (Summers [2003]); where one test result is the mean of at least two individual companion sample values, and*
$\overline{I_c}$ *= averaage (mean) of all* I_c *values*



Results of life- span assessment of EMR specimens at the Port. The required maintenance free life span is 50- years [1, 9].

The concrete casting beds and storage area at the Shaikh Khalifa Bin Sal man Port in Bahrain. Photo courtesy Posford Haskoning Consultants, designers and supervisors for the project.

Using the concept of relative life extension, it is possible to scientifically investigate the lifespan of the structure. The results of this process are presented in Fig 9. This chart includes cover transformations based upon research by Clear [16] and more recently Lounis and Amleh [17], as cover depths were increased from 50 to at least 75 mm at all locations of severe exposure.

CLOSURE

The use of the Frameworks concepts leads to low water content, lower binder contents, higher stone contents and normal strength development. This reduces heat and shrinkage and the associated risk of cracking. Yet mixtures can have a high workability and improved curing response, all factors that enhance constructibility and contribute significantly to overall project durability.

Performance data from the major deep water port illustrates that the approach has been highly successful, resulting in a substantial cost savings to the client with excellent strength and durability performance and virtually crack-free elements. A significant, contributing factor to the success of the project is the ability of the ready-mixed concrete producer to supply highly durable concrete of excellent workability with very low water content, excellent strength development characteristics, low heat development, low risk of cracking, and stripping times of just 2 to 4-days (depending on ambient temperature conditions). Of particular advantage was that concrete placement could continue 24 hours per day without interruption during the summer months, due to the very low heat profile of the concrete mixtures.

A wide range of projects have been built in Bahrain including 85 metre high, reinforced concrete coastal region industrial storage silos, high-rise buildings (42 stories or higher), major infrastructure including bridges and national pumping station schemes, all representing some US$2.5 billion of construction put-in-place within the last five years. Many other projects incorporating these concepts are now in their planning stages.

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About Superpozz

The binder at the Port consisted of 70 percent Portland cement, 30 percent Durapozz® (classified fly ash conforming to either BS 3892 or ASTM C 618 Type F that is manufactured by Ash Resources, South Africa) plus the addition of a highly reactive classified fine pozzolan identified as Superpozz®. Superpozz® is manufactured by Micron Materials (South Africa) and is exclusively marketed in Southeast Asia by Lafarge Cement Singapore. These products played a significant role in the advanced concrete technology of the port, as the overall characteristics of the blended binder and the addition of Superpozz® allowed the reduction of water in the mixture and enhanced strength, for a given workability. Such benefits are essential for project and concrete durability.

About the Author

G Robin Summers, PE, MSCE, a registered engineer in the USA, has more than 20 years of progressive experience in concrete construction. He was head of the Materials Testing and Research Department in Bahrain for nine years where he developed and directed the exploratory research activities on concrete and project durability. Presently living in the United Kingdom, he consults on concrete projects throughout the world and has published and presented on concrete technology and other engineering subjects on more than 100 occasions. In addition to his consulting activities, he is engaged in post-graduate research and the Civil and Computational Engineering Research Centre at the University of Wales, Swansea, where he continues to develop concepts on durable concrete.