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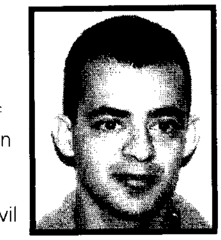
# The in-service performance of reinforced concrete culverts

**P Ronné and J Mackechnie**

***The increasing use of fast-track construction techniques in South Africa has led to precast portal culverts becoming an essential component of road infrastructure. Precast portal culverts are structural units used for the conveyance of water below final road level. Culverts occasionally in contact with water are subject to potential wet-dry cycles, which exacerbates the severity of durability problems. Despite this, the current specifications require 20-mm cover over reinforcement as sufficient to achieve durability.***

***A systematic study was undertaken in the Department of Civil Engineering, UCT, in order to study and quantify the long-term performance of these units in typical service environments. The results show that the performance of precast box culverts is variable, with a direct correlation existing between poor performance and aggressiveness of the environment. The performance of precast culverts is adversely affected in units where decreased levels of manufacturing quality are observed. Finally, a comparison is made showing that the concrete of precast culverts has superior quality to the concrete used to construct cast-in-place culverts.***



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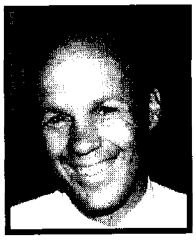

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## INTRODUCTION

Modern fast-track construction methods increasingly favour the use of precast concrete elements. The benefits of using precast elements include shortened on-site construction time, decreased time to recoup project costs (build-operate-transfer schemes), homogeneity of units and a guaranteed performance criterion.

Precast portal culverts can be considered structurally significant units for which the durability might be critical. Portal culverts are hollow, rectangular units used to convey water from the upstream to the downstream side of a watercourse crossing the path of a road. Since culverts pass under roadways, they are subject to a significantly important combination of traffic, earth and water loads. In environments like those of the Western Cape, culverts may be subject to repeated wetting and drying cycles. It is well known that wet and dry cycles exacerbate reinforcing steel corrosion and increase the risk of other durability problems. Essentially the durability of these units is important in providing the continued ability to resist the applied loads. Despite this, engineers and owners of these structures appear to have complete faith in the current specification to avoid the potential durability problems. Currently little is known about the long-term performance of precast box culverts apart from limited anecdotal evidence.

## CURRENT SPECIFICATIONS

Portal culverts are included in the national bridge design code, TMH 7 (1981) – Parts 1 and 2 (Code of Practice for the Design of Highway Bridges and Culverts in South Africa). The inclusion of culverts in this code underlines their structural importance in providing resistance to the applicable set of bridge loads. This implies that there is a reliance on a minimum level of resistance, which in turn needs to be guaranteed. Thus the durability of culverts is of the utmost importance, particularly with precast culverts, which are designed with a minimum cover to reinforcing steel.

## The SABS 986-1994 specification

The SABS 986 specification was revised in 1994 and was intended to form a cohesive, binding national standard for the construction of precast portal culverts. Previously, each local provincial administration and transportation department had their own requirements for precast portal culverts. The main focus of the document was to standardise the proof load requirements for precast portal culverts and to agree on suitable product testing arrangements necessary to guarantee the structural performance of the culvert for SABS certification purposes (SABS 986-1994). However, durability-related issues have not been rigorously addressed in this specification.

Historically, precast portal culverts have been afforded a significant reduction in concrete cover to reinforcement compared with cast-in-place concrete. The minimum cover allowed (SABS 986-1994) is the greater of 20 mm or the diameter of the reinforcement. In comparison, if the same unit were to be cast in-place, the minimum required cover would be 40 mm (or greater, depending on the exposure environment). The reduction in cover is supposedly a direct consequence of the superior factory manufacturing quality. Precast construction has the perceived advantage that a greater degree of uniformity and control can be achieved. The reduction in cover is a consequence of the increased quality control over the materials used, the mixing procedures, reinforcing steel arrangement and placement, and especially the control over the concrete casting, compacting and curing. In reality the quality of precast concrete (in terms of durability) must be as much as four times better than that of cast-in-place concrete to facilitate this reduction in cover.

Clause 4.1 of SABS 986 -(1994) states that portal culverts will be 'adequately durable if the reinforcement is protected by a concrete cover as specified', except if very aggressive groundwater or conveyed water is encountered. However, the durability of culverts may be compromised if the presumed quality control of the concrete is not achieved. Although some controls are in place, such as a minimum 28 day compressive cube strength of 40 MPa, a minimum cementitious content of 350 kg/m$^3$, and the guaranteed proof load on the final product, neither of these controls can be used in a manner to achieve durability of the final product. The durability, or resistance to adverse effects from the environment, can be generally described as a function of the cover to the reinforcing steel and the quality of the concrete in the cover region.

Currently there are no recommendations in SABS 986 (1994) to ensure a minimum level of durability. Nor is there any recommendation of the durability class required for particular environments. It is clear that there is a substantial difference in the requirements for a culvert to be used in a marine environment and a culvert destined for a largely dry environment. This decision is currently based on the judgement of the design engineer.

The service life of precast portal culverts will be affected by the quality of the manufacturing process, as well as the environment to which the culvert has been exposed and the period of time. The quality of the manufacturing process is a factor that should be controlled. However issues pertinent to such precast applications, with particular reference to the achievement of the required cover and the influence of accelerated curing procedures on concrete durability, have not been adequately addressed. For instance, generally accepted guidelines representing good accelerated (or steam) curing practices should be recommended (see Kellerman & du Preez, 1994).

## Other national building codes

The reduction in cover for precast concrete is also apparent in a number of other national codes. For example, the South African Transport Services Bridge Code (SATS 1983) recommends a minimum cover of 30 mm to be used for the inside faces of factory made culvert units in severe environments (defined in SABS 0100 (1992) - Part II). In comparison, the American building code ACI 318-95R recommends a reduction in cover from 50 mm for cast-in-place walls and slabs to 38 mm for precast concrete. The Australian construction code AS 3600 (1994) recommends a reduction in cover from 30 mm to 25 mm for precast members with the interior surfaces subject to repeated wetting and drying.

A reduction in cover to only 20 mm is not recommended in any other code of practice. Since the depth of penetration of most aggressive agents to concrete can be modelled as being approximately proportional to the square root of time, the effect of increasing the cover from 20 mm to 25 mm can increase the time taken to reach the reinforcing steel by more than 50 %. An increase in cover from 20 mm to 30 mm would more than double the time taken for an aggressive agent to reach the reinforcing steel. Thus highlighting the potential risk to the durability of precast portal culverts with design covers of 20 mm.

## INVESTIGATIVE METHODS USED

A visual inspection procedure was developed to categorise the main environmental influences on culverts in the Western Cape. Since very little is known about the in-service performance of box culverts, an important part of the method consisted of gathering sufficient information to accurately identify a particular structure. The use of the road stake value system was adopted to accurately identify the position of the culvert. The manufacturing details, particularly the precast manufacturer, construction date and size are necessary for comparisons to be made. This information facilitated follow-up studies, which were able to relate degradation with exposure time. Only culverts with height and span dimensions exceeding one metre were considered for this investigation as inspection of smaller units proved awkward.

The characterisation of the exposure (macro) environment was based on general grouping of typical environments in accordance with recommendations of CEB (1992). However, marine environments were further classified in accordance with Mackechnie (1997), thereby accounting for the potential influence of strong local winds on the distribution of airborne chlorides from the sea.

The in-service performance was assessed with the use of a rational checklist of critical factors, which included recording the quality of the concrete surface, the presence of telltale stains and physical evidence of distress. Signs of surface damage that can be easily identified include honeycombing (indicates poor construction techniques) and spalling (indicates corrosion of reinforcing steel). Stains often present telltale signs of rebar corrosion (rust stains) or alkali-silica reaction (presence of gel). Abrasion damage due to sediment transport (including small boulders), as well as the erosive effects of softwater attack, is another visually identifiable sign of deterioration.

Cracks may appear in reinforced concrete structures due to a variety of reasons. Cracks were recorded by their surface width with the use of a crack comparator. The interpretation of cracks with regard to the potential adverse effect on the durability of the structure remains a contentious issue. However, structurally significant cracks were defined as having a surface width of greater than 0,5 mm.

Since manufacturing quality issues are critical to the performance of precast culverts, a cover-depth survey of two selected units from each culvert structure was performed, and an in situ carbonation depth measurement was also recorded. Carbonation testing was conducted by removing a small section of the concrete surface and then spraying with a 1% phenolphthalein in 50/50 ethanol/water solution. The average distance from the structure's outer surface to the colour change was recorded. This distance represents the zone of concrete, which has reduced alkalinity as a result of reactions with carbon dioxide gas of the atmosphere. Carbonation is not detrimental to concrete, but the lowering of the pH is sufficient to depassivate embedded steel and allow corrosion to occur.

The depth or thickness of cover survey was carried out using an electronic cover meter along longitudinal lines as shown in figure 1. A simple statistical analysis of all the depths of cover achieved was later calculated. The cover measurements were analysed by calculating the mean and standard deviation for the representative inner culvert surface. Most importantly, from the durability perspective, the number of reinforcing bars with less than 20 mm cover was noted. The analysis was conducted with collated data as the entire inner culvert surface is presumed to have the same durability risk. Occasionally it was impossible to reach the soffit of the structure without the use of a stepladder. In such cases, data were only calculated for the wall sections. The outer surfaces of the culvert have been excluded from this particular study, as they are inaccessible and remain enclosed by the road pavement layers.

## FINDINGS

The deterioration of culverts was summarised in terms of the individual units. In total 1 313 units were surveyed, of which 498 units (38%) exhibited some sign of deterioration. The physical manifestation of deterioration was classified in terms of abrasion, staining, spalling and cracks as shown in figure 2. Likely causes for this deterioration were interpreted as

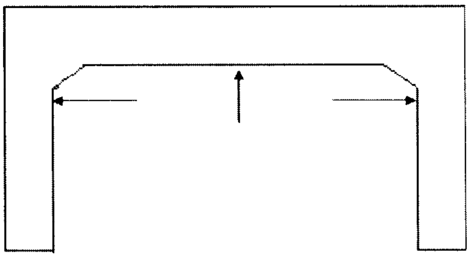

*Figure 1 Lines, indicated by arrows in cross sections, along which cover to steel was checked*

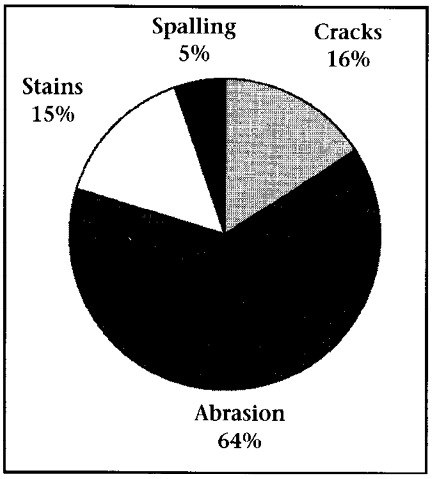

*Figure 2 The physical manifestations of observed deterioration of precast culverts*

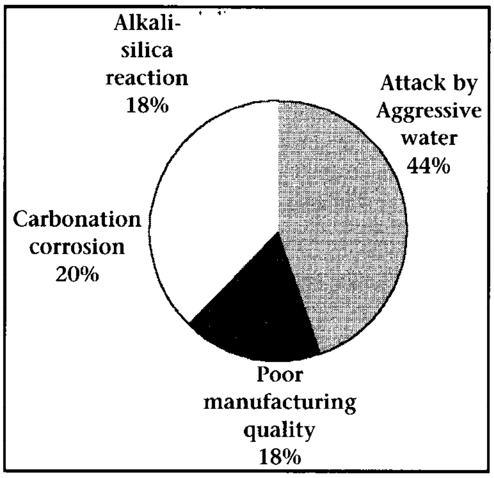

*Figure 3 The likely causes of damage to precast culverts*

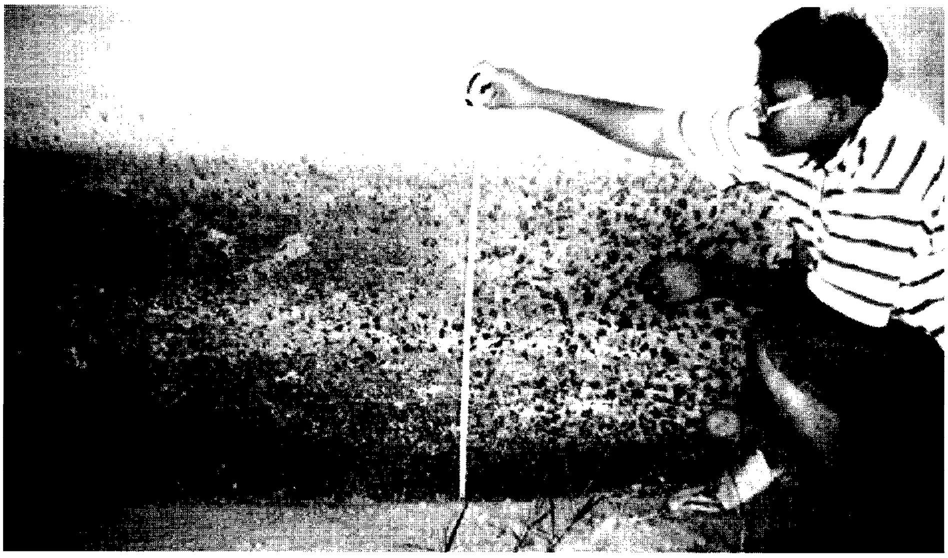

*Figure 4 Soft-water attack with constant removal of softened layer*

either alkali-silica reaction, carbonation corrosion, attack by aggressive waters or poor manufacturing quality as shown graphically in figure 3. Surface attack due to presence of 'ion hungry' soft-water, prevalent in the Western Cape, formed an overwhelming portion of this deterioration.

In instances where corrosion staining was noted and carbonation depth exceeded the cover achieved, carbonation corrosion was attributed as the likely cause. A significant number of culverts showed signs of distress due to alkali-silica reaction. This is due to the fact that rich concrete mixes are used in an effort to gain high early concrete strength. The maximum alkali content, for use with reactive greywacke aggregate, may have been exceeded due to normal batching variations. However, alkali-silica reaction will only develop fully if sufficient moisture is present in the concrete. A point of concern was that a significant portion of deterioration could be directly linked with poor manufacturing quality. Poor manufacturing quality was defined as reinforcing bars with covers less than 10 mm and or blowholes at least 5 mm deep. In both these instances, the effective cover has been reduced, such that the reinforcing steel is not fully protected by the cover concrete.

## Evidence of soft-water attack

Soft-water attack is a frontal phenomenon in which calcium ions are leached from the concrete matrix (Basson & Ballim 1994). This leads to a layer of softened concrete being formed at the surface, which may be easily removed through scour action by passing water. An example of soft-water attack with exposed aggregates to a height on a vertical surface of approximately 1 m is shown in figure 4. The depth of the softened layer was found to be 3 mm as determined from core samples taken from an unscoured section of the culvert. Thus soft-water attack is found to be significant if the softened portions are periodically eroded.

## Effect of sulphate ions in the environment

The ingress of mild concentrations of sulphate ions is sufficient to cause widespread distress as shown in figure 5. Large portions of cracking and spalling, together with the presence localised areas in which the cement paste has been removed and the simultaneous presence of white efflorescent markings, are evident throughout the culvert. In areas of localised disintegration of the cement paste, the concentration of sulphate ions (expressed as SO3 by mass of cement) was found to be as high as 2,5%, while background sulphate levels were found to be in the order of only 1,3%. Although an SO3 content of 2,5% is the maximum allowable sulphate content for ordinary Portland cements (SABS ENV 197 - 1992), severe deterioration of the culvert was observed. An extracted core sample, as shown in figure 6, taken from the culvert structure depicted in figure 5 highlighted the erosion of the cement paste, the severe corrosion of a reinforcing bar at low cover, and severe cracking associated with this sulphate-related deterioration. A crack, 1 mm wide, extending 98 mm into the core was found to have formed as a result of the corroded reinforcing steel. The observed corrosion was probably assisted by the depassivation of the steel due to the sulphation process. The sulphation process reduces the alkalinity of concrete, similarly to the carbonation process, but is often associated with the spalling of concrete as a result of sulphate attack (Basson & Ballim 1994). The sulphation depth, determined using a 1% phenolphthalein in 50/50 ethanol/water solution, was 26 mm from the exposed inner culvert surface. The combined effects of salt crystallisation and mild sulphate attack probably caused the observed surface damage and erosion of the cement paste.

## Effect of chloride ion penetration

Although no culverts in very severe marine environments were inspected during the course of this study, culverts containing a 50/50 Portland cement/ground granulated Corex slag (GGCS) blend with 20-mm cover have recently been installed in a housing development at the V&A Waterfront in Cape Town. In moderate marine environments chloride ions were found to readily diffuse through conventional ordinary Portland cement concrete culverts, and reached a sufficient concentration (0,4 % $Cl^-$ by mass of cement) at the level of the reinforcing steel to activate corrosion (Mackechnie 1997). A typical profile taken from a relatively dry and unaffected end unit in a moderate marine environment is shown in figure 7. The evidence suggests that the chloride ions have diffused from the backfill material. Samples taken from one of many spalled areas near the water level of the same structure exhibited surface (0 to 10 mm) chloride ion concentrations of 1,6 % $Cl^-$ by mass of cement. Judging by the large number of units exhibiting spalling and corrosion, it is obvious that sufficient chloride ion (above 1,0 % $Cl^-$ by mass of cement (Mackechnie 1997)) exists at the reinforcing steel to sustain high levels of corrosion.

*Figure 5 A severely distressed culvert exhibiting sulphate attack*

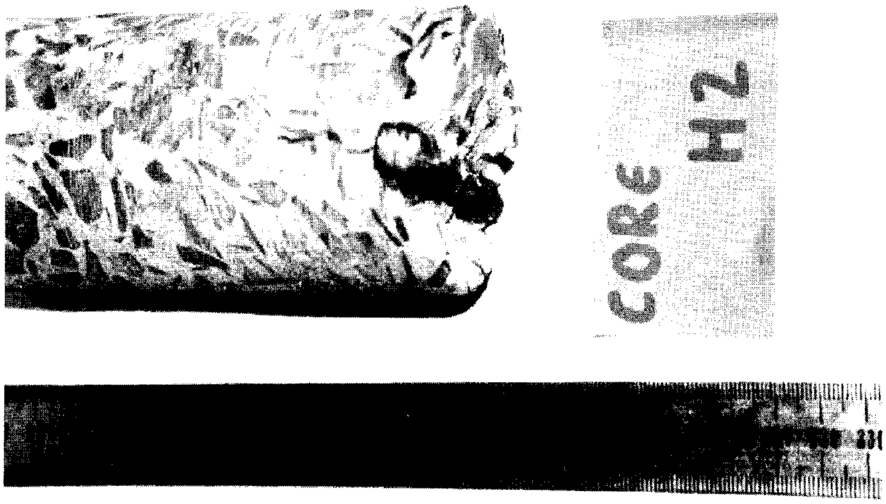

*Figure 6 A horizontally drilled core sample taken from a side (wall) of a severely distressed unit exhibiting sulphate attack. The labelled end represents the inner face of the culvert*

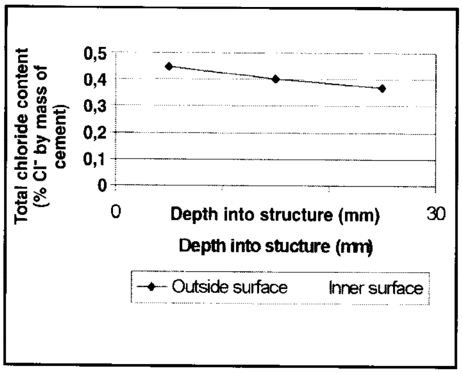

*Figure 7 Chloride ion profile of a largely unaffected unit in a moderate marine environment*

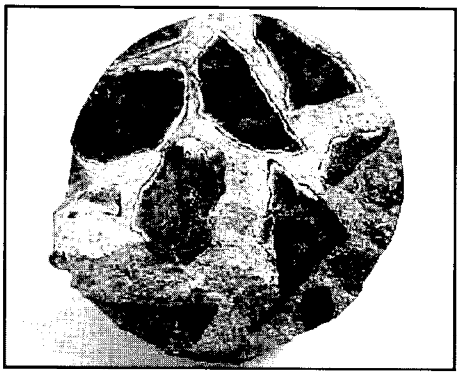

*Figure 8 White alkali-silica reaction products rimming reactive greywacke aggregate on a core sample (45-mm diameter)*

## Alkali-silica reaction

Alkali-silica reaction should be completely preventable by either avoiding the use of reactive aggregates, or limiting the alkali content to acceptable limits with the use of reactive aggregates (Oberholster 1994). However, limiting the alkali content contributed by the cement may not be sufficient if an external source of alkalis exists. If sufficient alkali and a reactive aggregate are present, the severity of the reaction is aggravated by the presence of moisture. The typical crack pattern, the presence of white gel products and the continually wet appearance of cracks characteristic of alkali-silica reaction are some of the telltale signs that alkali-silica reaction may be present (Oberholster 1994). The presence of the typical white reaction products on the facture surface of an exploratory core together with a noticeable concentration of reaction products rimming greywacke aggregate was confirmed and is shown in figure 8.

## Carbonation testing

Data obtained from in situ carbonation tests were entered into a carbonation model, from which a carbonation coefficient, normalised for exposure time, was calculated. This allowed the comparison of carbonation rates of precast and cast-in-place concrete. The rate of carbonation was modelled using equation 1:

$$Dc = Kc * t^{x} \qquad (1)$$

where Dc is the depth of carbonation front in mm

Kc is the carbonation coefficient (mm/year$^{x}$)
t is the exposure time in years
x is a constant (typically between 0,33 and 0,5)
Mackechnie (1999) suggests the use of 0,4 as the most appropriate value

Through the use of this empirical equation to determine the carbonation coefficient, an indication of the material quality of the concrete may be attained (Mackechnie 1999). The computed coefficient can also be used to predict future carbonation depths with time. The mean carbonation coefficient for precast box culverts was found to be 3,0 mm/year$^{0,4}$, and a highest carbonation coefficient value of 7,5 mm/year$^{0,4}$ was determined. Figure 9 represents the corresponding carbonation profiles plotted for a period of 30 years. In comparison, the carbonation coefficient of laboratory grade 40 OPC concrete exposed to a mild outdoor carbonating environment was found to be 3,2 mm/year$^{0,4}$ (Mackechnie 1999).

## Achievement of cover over reinforcing steel

Despite all of the above findings, the lack of achievement of the required 20-mm cover is the most frequently observed problem. Units constructed by three of the largest precast culvert manufacturers, denoted by P, R and T, showed a consistent trend in the lack of achievement of cover:

P: 9 out of 20 units tested were found to have at least one reinforcing bar less than the required 20-mm cover with a maximum of 9 bars of low cover found for one particular unit.
R: 21 out of 41 units had low covers, with a maximum of 11 bars of low cover found for one particular unit.
T: 20 out of 36 units had low covers, with a maximum of 7 bars of low cover found in one particular unit (as depicted in figure 10).

Excessive variability of cover, as measured by the variability of the mean cover values, was also found to exist. The coefficient of variation, determined by expressing the standard deviation as a percentage of the mean, was used to gauge the degree of manufacturing control that was historically achieved (Sharp 1997). The

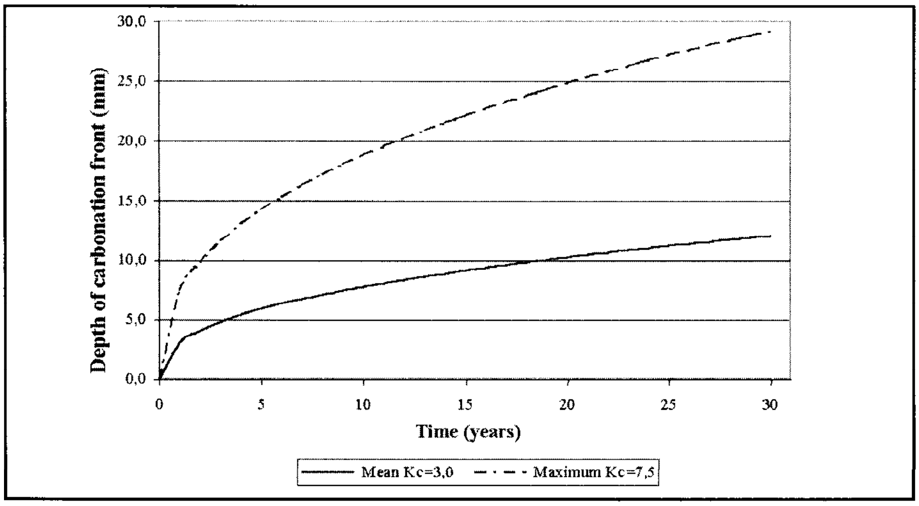

*Figure 9 Carbonation profiles calculated for precast portal culverts in the Western Cape*

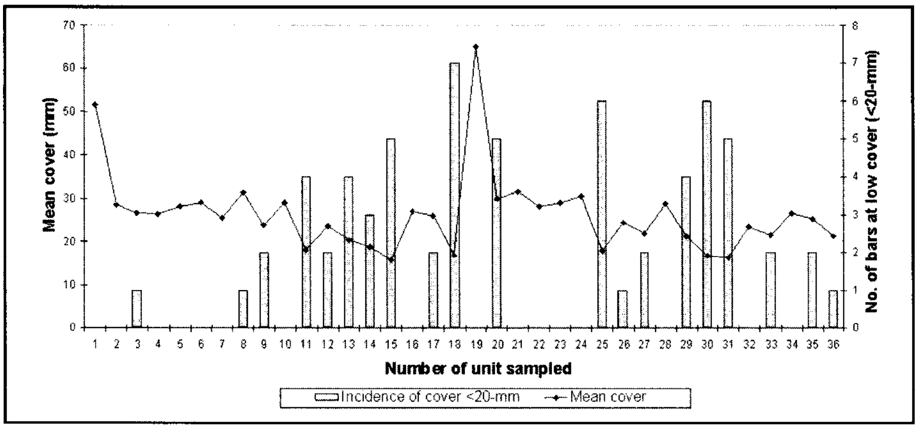

*Figure 10 Historical analysis of cover achieved - Manufacturer T*

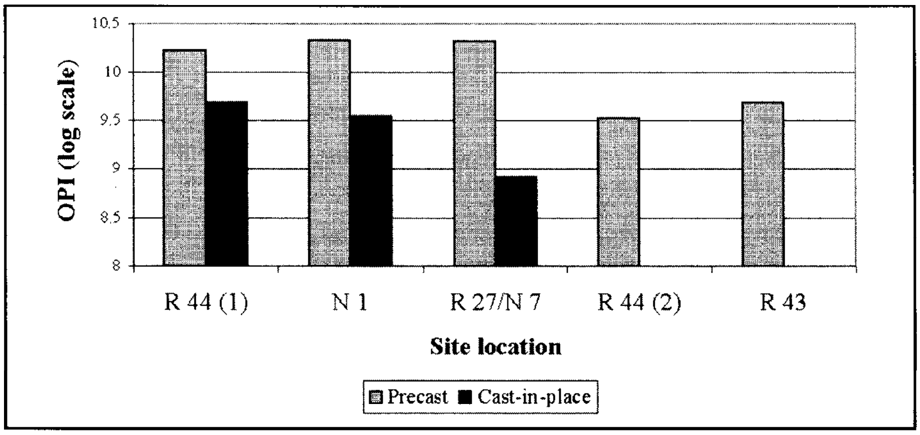

*Figure 11 Oxygen permeability index to determine concrete quality*

coefficients of variation of cover should be less than 15% for good factory control (Sharp 1997) but were on average 23% indicating fair control. A considerable number of units were found to have a coefficient of variation of more than 30% indicating poor control.

# COMPARISON OF THE PERFORMANCE OF CAST-IN-PLACE AND PRECAST CULVERTS

It has not been possible to obtain the construction date of cast-in-place culverts, thus making age or rate of attack comparisons very difficult. The oxygen permeability index (OPI) was determined to compare the general quality of the relevant concretes used in box culvert construction. Alexander *et al* (1999a) make the point that OPI is suited to assessing compaction since it is particularly sensitive to changes in the coarse pore fraction. OPI has also been shown to broadly correlate with carbonation depth (Alexander *et al* 1999b). OPI was determined by measuring the gas (oxygen) permeability of an oven-dried concrete. Core samples were obtained from actual structures from which slices of the uncarbonated concrete were prepared and tested in accordance with Alexander *et al* (1999a). The results are shown graphically in figure 11.

Significant differences in overall concrete quality, as measured by the OPI, were found to exist between precast and cast-in-place concrete. Generally, precast concrete achieved significantly better OPI values in excess of 10,20, while cast-in-place concrete achieved OPI values between 8,91 and 9,68 (OPI values measured on a logarithmic scale) indicating that cast-in-place concrete is more permeable than precast concrete. Figure 11 shows that from the locations tested precast concrete is of better quality and compaction than cast-in-place concrete. Concretes with OPI greater than 10 represents excellent durability class, while OPI between 9,5 and 10 represents good durability class (Alexander *et al* 1999b). Site locations R43 and R44(2) exhibited large carbonation coefficients, as measured using the *in situ* carbonation test; a decrease in the quality of those particular precast units was found as measured by a decrease in OPI values. The lowest OPI value achieved for precast concrete was approximately equal to the highest OPI value achieved for cast-in-place concrete.

# CONCLUSIONS

It is clear that the current precast-culvert specifications are not conservative when compared to similar national and international codes. A reduction in the cover requirement, based on the expected improved concrete quality is acceptable. However a cover as low as 20 mm seems extreme based on the potential durability risk of the structure.

A large proportion, 38%, of all precast culvert units surveyed exhibited some degree of deterioration. The occurrence of alkali-silica reaction should be completely preventable by applying sound concrete mix design principles. Soft-water attack is unlikely to cause serviceability failures, even where turbulent water is encountered, but allowance should be made for this type of attack. Carbonation corrosion was a frequent occurrence, due to the low covers and exposure to frequent wetting and drying cycles. Precast culverts with 20-mm cover are very susceptible to mild concentrations of aggressive ion species, particularly in chloride- and sulphate-rich environments.

Poor manufacturing quality, particularly low cover, was responsible for a significant portion of the deterioration observed. Generally, rates of carbonation were low, except where aggressive microenvironments and lower manufacturing quality were encountered. An average carbonation depth of 12 mm can be expected after 30 years in the Western Cape. Measurement of the covers achieved historically shows a significant lack in control of reinforcing steel placement. A nominal reduction in cover with precast concrete is justified since the quality of precast concrete is superior to cast-in-place concrete as determined by OPI measurements. However, the actual reduction in cover should be viewed in relation to the manufacturing quality currently achieved in precast factories.

## Note

This paper is based on Philip Ronné's MSc(Eng) dissertation, which has been passed by the Faculty of Engineering and the Built Environment (Department of Civil Engineering) at the University of Cape Town in 2000. Additional contents of the dissertation included the assessment of the current manufacturing quality of precast portal culverts and a laboratory study to quantify the effect of steam curing on concrete durability.

## Acknowledgements

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