# 1
# Introduction: key issues in the non-destructive testing of concrete structures

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**Abstract**: In-place testing of concrete structures to assess durability performance plays an important role in establishing long-term infrastructure maintenance strategies. This role is considered in detail, together with the development of relevant non-destructive test methods and associated 'Standards' over the past 40 years. Examples of driving factors are given together with illustrative industrial case studies, including maintenance strategies, based on UK experience over that period. Particular attention is given to the role of international organisations and national industrial bodies in development and dissemination of authoritative guidance documentation, including recently introduced European Standards.

**Key words**: infrastructure, structural concrete, in-place testing, durability performance, standards.

## 1.1 Introduction

Infrastructure is what supports our daily life: roads and harbours, railways and airports, hospitals, sports stadiums and schools, access to drinking water and shelter from the weather. Infrastructure adds to our quality of life, and because it works, we take it for granted. Only when parts of it fail, or are taken away, do we realise its value.[1]

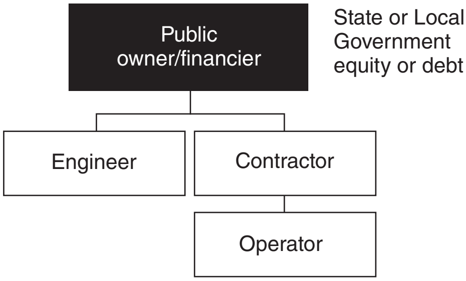
## 1.2 Design, build and maintain

Concrete is, because of its versatility, comparative cheapness and energy efficiency, of great and increasing importance for all types of construction throughout the world. Concrete structures can be durable and long lasting but to be so, due consideration needs to be given at the design stage to the effect that the environment to which the structure will be exposed will have on the concrete. Degradation can result from either that environment, for example frost damage, or from internal causes within the concrete as in alkali–aggregate reaction. It is also necessary to distinguish between degradation of the concrete itself and loss of protection and subsequent corrosion of the steel reinforcement. The *ACI Committee 201*[2] defines concrete durability as: *'its resistance to deteriorating influences which may through* *inadvertence or ignorance reside in the concrete itself, or which are inherent in the environment to which it is exposed'.*

Initially, concrete was regarded as having an inherently high durability, but more recent experiences have shown that this is not necessarily the case unless durability design forms an integral part of the design and construction process. There is a need to consider all potential deterioration mechanisms at the design stage in order to select and specify an appropriate concrete mixture from a durability perspective.[3] The prescriptive specification for concrete based on permissible maximum water–cement ratio and minimum cement content has received much criticism in recent years. It may even have inadvertently allowed designers and contractors to avoid having to consider or implement all the available information required for a sound design for durable construction. This includes careful attention to drainage and detailing to minimise the effects of water, which is a key transportation and fuelling agent, upon materials. Unexpected maintenance and repairs arising very early in the specified service life of structures has caused enormous financial burdens to clients. The expectation of the owner of a structure is that it will only require very little or no maintenance during its design life. The owners have realised that the *cheapest option* for constructing a structure may work out to be an *expensive option* in the long run.

Owners have sought ways of minimising project risks to themselves. The design–bid–build delivery system was the norm where the owner contracted separately the design and construction of a project. However, they then adopted design/build delivery systems where from inception to completion only one organisation is liable to the owner for defects, delays, and losses. Streamlining the delivery system reduced the delivery time of the completed project by forcing consultancy/design teams and contractors/construction companies to form collaborations and complete the separate tasks at the same time, i.e. working in parallel. This system is used to minimise the project risk for an owner and to reduce the delivery schedule by overlapping the design phase and construction phase of a project.

However, this approach does not take 'life cycle costing' into account. The benefits of 'life cycle costing' are particularly important, as most infrastructure owners spend more money maintaining their systems than on expansion. In addition, the life-cycle approach removes important maintenance issues from the political vagaries affecting many maintenance budgets, with owners often not knowing how much funding will be available to them from year to year. In such cases, they are often forced to spend what money they do have on the most pressing maintenance needs rather than a more rational and cost-effective, preventive approach. Major infrastructure projects have now moved to design–build–operate (maintain) or 'turnkey' procurement, e.g., the US Department of Transportation – Federal Highway




*1.1* Design–build–operate (maintain).[4]

Administration[4] defines it as an integrated partnership that combines the design and construction responsibilities of design–build procurements with operations and maintenance, see Fig. 1.1.

The advantage of the design–build–operate (maintain) (DBOM) approach is that it combines responsibility for usually disparate functions (design, construction, and maintenance) under a single entity. This allows the private partners to take advantage of a number of efficiencies. The project design can be tailored to the construction equipment and materials that will be used. In addition, the DBOM team is also required to establish a long-term maintenance programme up front, together with estimates of the associated costs. The team's detailed knowledge of the project design and the materials utilised allows it to develop a tailored maintenance plan that anticipates and addresses needs as they occur, thereby reducing the risk that issues will go unnoticed or unattended and then deteriorate into much more costly problems.

Few structures collapse in the UK but when they do the consequences and ramifications are huge. 'Avoid the complacency which leads to tragedy', was the central theme of the Standing Committee on Structural Safety's 12th bi-annual report.[5] However, lack of attention to due consideration of durability criteria in the design and specification of structures in the past has led to a thriving and expanding repair industry in recent years, see Fig. 1.2,[6] and design for ease of inspection and maintenance should be regarded as an important issue.

## 1.3 Role of in-place testing

The principal driving force for the numerous developments of non-destructive testing (NDT) methods and equipment has, of course, been the requirements of industry worldwide to meet both specific short-term needs and longer-term maintenance strategies. Although reports of some techniques date back to the 1930s from Russia, key early developments of

**Concrete repair on the increase**

BY JOHN LEITCH

CONCRETE REPAIRS are on the increase. The value of work completed by members of the Concrete Repair Association during the first half of 1995 was a 'marked improvement' on the previous six months.

The latest CRA state of trade survey, published this week, shows a lift in enquires from all sectors – private, public and civil engineering.

A CRA spokesman said: 'This is the fifth half-yearly survey we have conducted. The first three showed a buoyant industry, although the results of the fourth one were bad. The latest shows that things are getting better.'

Encouragingly, the new figures reveal that the interval between enquiries being received and work being let shortened for the first time in three years. However, contractor members report no change with regard to repair work in hand.

The UK concrete repair market is worth £130 million a year. After expansion in 1993, the second half of 1994 brought a large downturn in workload which has left margins under pressure.

Concrete repair is primarily connected with refurbishment work.

Enthusiasm for the improvement in the value of concrete repair work in 1995 is muted by the fact that the number of contracts completed during the period fell significantly. The main cut back was in larger value projects.

Half of CRA's members are working at less capacity than they expected. They expect no improvement in profit margins over the forthcoming 12 months and are pessimistic about work volumes.

The UK concrete repair market is worth £130 million a year

*1.2* Thriving and expanding repair industry in the UK.[6]

surface hardness, radiography, nuclear and vibration methods together with pulse testing using hammer blows and ultrasonic techniques took place on both sides of the Atlantic during the 1940s and 1950s. The first comprehensive textbook on the subject devoted entirely to concrete was published in the UK by Jones, who was one of the pioneers of the subject.[7] He considers all these approaches, although concentrating on vibrational and pulse methods, with the aim of 'providing a reliable estimate of the quality of concrete in the structure without relying solely on test specimens that are not necessarily representative of the structural concrete'.

At this stage, nearly all these techniques were at an experimental stage, with very limited industrial usage or experience, although principles and background theory are well-established. In 1969, a 'Symposium on Non-destructive Testing of Concrete and Timber' was organised in London[8] jointly by the Institution of Civil Engineers and the British National Committee for NDT, and was the first significant event of its type (certainly in the UK). Progress through the 1960s had clearly been relatively limited and industrial take-up, even of established methods such as ultrasonic pulse velocity, had been slow. A feature of the discussions is the reluctance of engineers to adopt *in situ* testing unless mentioned in British Standards, with the first tranche at draft stage. The more extensive experience and practical application in Eastern Europe was evident, especially in the use of combined methods for strength estimation. Durability testing was a new feature although corrosion of reinforcing steel receives only one passing mention relating to radiographic inspections. References are also made to pull-out methods for strength estimation and early magnetic covermeters. At this stage, there is, however, clear recognition of the limitations of many of these techniques, as well as the influence of variability of *in situ* concrete properties upon interpretation of results.

## 1.4 Developments of non-destructive testing methods in the 1970s

The initial group of seven British Standards were published in the 1970s, lending respectability both to the test methods and the concept of *in situ* testing. The current equivalent British Standards are shown in Table 1.1. Two other major factors, however, provided the key impetus in the UK.

### 1.4.1 Collapse of high-alumina-cement pre-tensioned beams

In 1974, several high-alumina-cement pre-tensioned beams in the UK collapsed as a result of major loss of concrete strength owing to the 'conversion' of the high-alumina-cement concrete under unfavourable environmental conditions. This led to a nationwide programme of inspection and

*Table 1.1* Current British Standards

| | |
|---|---|
| BS 1881: Testing concrete | Part 5: 1970 Methods of testing hardened concrete for other than strength |
| | Part 122: 1983 Method for the determination of water absorption |
| | Part 124: 1983 Chemical analysis of hardened concrete |
| | Part 130: 1986 Temperature matched curing of concrete specimens |
| | Part 201: 1986 Guide to the use of NDT for hardened concrete |
| | Part 204: 1986 The use of electromagnetic covermeters |
| | Part 205: 1986 Radiography of concrete |
| | Part 206: 1986 Determination of strain in concrete |
| | Part 207: 1992 Near to surface test methods for strength |
| | Part 208: 1996 Initial surface absorption test |
| BS 6089: 1981 | Assessment of concrete strength in existing structures (under review) |

*In February 1974 the collapse of the school roof beam at the John Cass School, Stepney, perhaps demonstrated their (many professionals in the construction field) concern, and this near-tragedy sparked off the current alarm which is now so prevalent in this country.*

*Thousands of home owners in my constituency and throughout the country have tried to put their property on the market and have been greeted with an opening question from a potential buyer "Does it contain HAC?" If the answer was "Yes", it is distinctly probable that the negotiations ended abruptly.*

*Then there are people seeking a mortgage who find that not all the building societies like to see the phrase "high alumina cement" in the surveyor's report, and a fee is wasted. There are people working in buildings which have stood the test of time—for two decades, perhaps—with HAC, but suddenly they develop concern because of the bandwagon effect. At present rumour and concern are rife and I am convinced that the Government have a clear duty to hasten their findings and urge upon the Building Research Establishment that the direction of its investigations warrants a 24-hour day until its research and advice is made known to this country. The cost to the nation could be enormous when taking into consideration the loss of amenity. There is also disruption of education and the concern of parents for the safety of their children. It is estimated that Birmingham alone could cost over £10 million to strengthen or replace the buildings. It is estimated that 22,000 buildings could well be involved. Newspapers and the mass media carry the claim that this programme could cost £2,000 million to remedy. The speculation is endless, in private, in the local authorities, and elsewhere.*

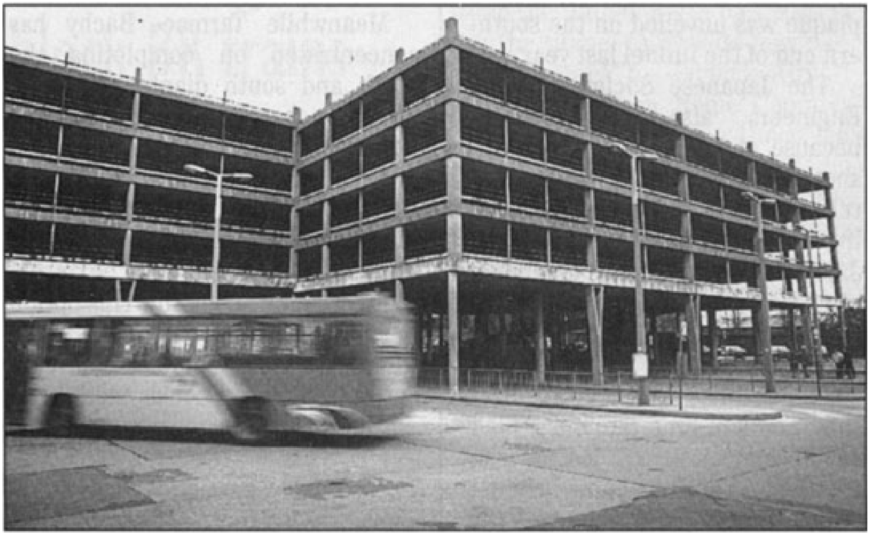
*1.3* High alumina cement (Commons Sitting, HC Deb 09 May 1975 vol 891, cc1893–906).[9]

assessment, see Fig. 1.3,[9] and the limitations of available non-destructive methods were apparent. Member cross-sections were often small; thus core-cutting was not always a viable proposition. Ultrasonic pulse velocity testing was, however, shown to offer possibilities for comparative purposes and was widely used. The need for new *in situ* strength tests led to the development of pull-off and internal fracture methods, together with increased interest amongst engineers of the possibilities of *in situ* testing more generally.

### 1.4.2 Corrosion of reinforcing steel

Deterioration as a result of the corrosion of reinforcing steel, often in relatively new structures, became an increasingly common phenomenon and led to development of improved cover measuring devices, air and water permeability tests and early work on electrical methods to assess the corrosion risk. Some examples are useful in highlighting the extent of the problem.

*The Queen Street car park*, Colchester (see Fig. 1.4), was constructed in 1971, but by 1985 there was evidence of corrosion of precast concrete units



*1.4* Multi-storey car park in Colchester is to be pulled down because concrete corrosion problems are beyond economic repair.[10]

on the *in situ* concrete frame with 3% of units found to be affected; repair recommendations were made to prolong the life of the car park by five years. In 1992, the car park, which sits over a busy bus station, was closed for safety reasons, 40% of units now being found to be affected. Refurbishment costs were put at £1.5M, rebuild at £3M and demolition at £350,000. The decision was taken to demolish the car park.[10]

*The M4 viaduct in west London*[11] was built in 1967 and began showing signs of deterioration in the 1990s, see Fig. 1.5(a). Inspections revealed that de-icing salts used on the M4 in winter had seeped past the road deck's asphalt plugs at the joints, see Fig. 1.5(b), and penetrated the concrete of the beams, causing the near-surface reinforcement to corrode. There was no immediate structural concern because there was a significant amount of redundancy in the crosshead beams. However, a programme of regular monitoring was introduced and concrete was removed from the crosshead beams over badly corroded reinforcement. In parallel, the Highways Agency began trialling different protection methods to arrest corrosion. For a proper repair all the chloride contaminated concrete, i.e. the whole pier, had to be removed. The alternative solution was to use electrochemical methods, e.g., cathodic protection, which requires an anode, on the surface or in the concrete, which is connected to a low voltage dc power supply. This minimises concrete repair to replacement of damaged material, saves cost of materials, reduces the duration of the repair work, and minimises the need for temporary support.

(a) (b)

*1.5* M4 viaduct in west London: (a) corrosion problems are apparent, and (b) the leaking joint above the crosshead beam.[11]

Installing cathodic protection using traditional discrete anodes would normally have required holes to be drilled from the underside of the cross-head beams. Fifty-eight anodes per beam would have had to be installed. Unable to get to the underside of the beams during the day and prohibited from drilling at night by noise limits, drilling the holes could have brought the project to a halt. Instead of drilling multiple holes, the suggestion was made to core a single hole from end to end of the beam, right through its centre, and avoid working beneath it at all. Drilling time for the single hole-through-the-middle approach was three days compared to 30 days or more for a conventional approach.

Interest in concrete strength assessment was also generally strong during the 1970s; the Concrete Society published a report on Core Testing in 1976[12] and detailed studies on 'small' cores were undertaken at the University of Liverpool.[13] The period was also marked by the publication in the USA of a key ACI Monograph[14] which was of much broader scope than previous books.

## 1.5 Further research on non-destructive testing methods in the 1980s

The 1980s was a period of significant activity when many of the techniques developed in the previous decade were the subject of further research (including work at the University of Liverpool) and became established in practice. Examples include half-cell potential and resistivity testing to assess corrosion risk, as well as pull-out and pull-off methods for *in situ* strength estimation. In particular, the Lok-test attracted considerable interest for *in situ* strength development monitoring. Detailed studies at the University of Liverpool on the effects of prestressing and reinforcing steel on ultrasonic pulse velocity measurements followed from the concerns over high alumina cement.

Elsewhere, the 'Figg' method for air and water permeability was also further developed for site use, and new methods included accelerated wear devices for *in situ* abrasion resistance testing. In North America, a major ACI Conference[15] included 38 papers on wide-ranging topics including sub-surface radar, thermography and acoustic emission, but with a strong emphasis on strength estimation. The first UK Standard on *In situ* Strength Assessment (1981), see Table 1.1, and the first book on in-place concrete testing for 20 years[16] were published. These were followed by major revision and upgrading of the relevant testing British Standards as indicated in Table 1.1, together with a major Addendum to the Concrete Society Core Testing Report in 1987. As in the 1970s, significant 'service failures' stimulated inspection and testing activity.

### 1.5.1 Collapse of post-tensioned beams

Bridge owners have for many years, been concerned about the corrosion of prestressing cables and the difficulty of inspection. These concerns were highlighted in December 1985 with the sudden collapse of a 32-year-old 18.3-m span post-tensioned segmental road bridge in South Wales.[17] The failure of the Ynys-y-Gwas Bridge, see Fig. 1.6, was directly caused by tendons corroded by chlorides from de-icing salts. The salt penetration was

*1.6* Collapse of the Ynys-y-Gwas bridge led to a ban on grouted tendons.[17]

eventually attributed to a combination of inadequate tendon protection, poor workmanship and ineffective deck waterproofing. Other key factors identified included the lack of an *in situ* top slab and joints opening under load.

Although possibly the most newsworthy, this is by no means the only bridge to have had problems. In September 1992, the Department of Transport's concern as an owner and client led to the announcement of a temporary ban on the commissioning of any new bridges of the 'grout duct post-tensioned type' until specifications had been reviewed. Construction of some bridges, already designed using bonded internal prestress, was allowed to continue. The Department of Trade's decision in effect laid down a challenge to the UK concrete bridge industry to put its house in order and to be able to demonstrate it had done so. The response by the Concrete Society, supported by the Concrete Bridge Development Group, was to set up a working party in June 1992 to study the problem and prepare recommendations. In May 1994, the working party held a seminar which summarised the position at that time. Detailed discussions started with the Highways Agency in April 1995 with a view to making use of the revised design and construction procedures,[18] to allow a phased re-introduction of bonded post-tensioned bridges.

The Ynys-y-Gwas bridge collapse did not only highlight existing concerns about corrosion of prestressing steel resulting from inadequate grouting of ducts, but it also highlighted the difficulty of inspecting them. This led to extensive programmes of field inspection, which again highlighted the limitations of available methods and stimulated work on new testing approaches that continued into the 1990s. The Highway Agency has recently included this challenge in their Advice Notes on NDT (see Table 1.2).

### 1.5.2 Alkali–silica reaction (ASR)

Problems of deterioration resulting from the moisture-sensitive expansive alkali–silica reaction (ASR) emerged in many parts of the UK and highlighted the need for appropriate test methods. These were primarily based on expansion testing of cores and petrographic examination of samples removed from the structure. Ultrasonics, including pulse attenuation studies, offered potential for laboratory use but were of limited value on site. Some examples are now given of structures suffering from ASR.

#### *Marsh Mills viaducts*

*The Marsh Mills viaducts*, according to the New Civil Engineer,[19] were 'condemned to a lingering but terminal decline'. Revelation that Marsh Mills viaducts were afflicted by the ASR came as a surprise. The industry

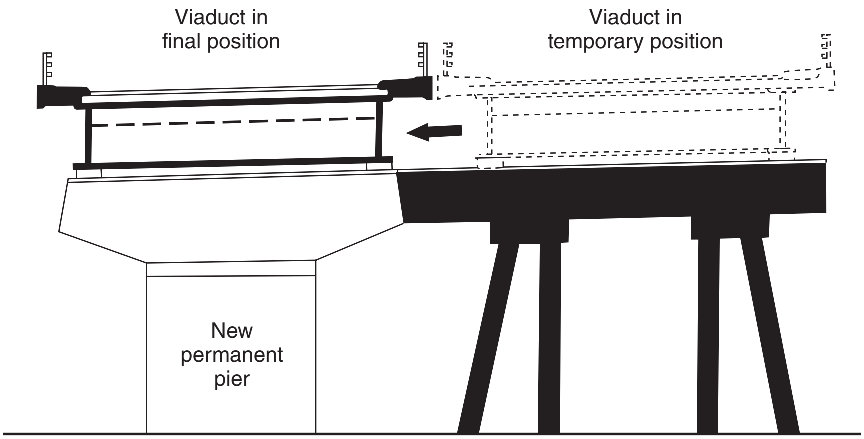
*Table 1.2* Recent UK guidance documents

| | |
|---|---|
| British Cement Association | 2002 Early age *in situ* strength assessment: Best Practice Guide |
| C.I.R.I.A. | TN143: 1992 Guide to test equipment<br>Rep 136: 1995 Formwork striking times criteria, prediction and methods of assessment |
| Concrete Society | TR48: 1997 Radar testing of concrete<br>TR60: 2004 Electrochemical tests for reinforcement corrosion<br>Proj. Rep 3: 2004 *In situ* concrete strength |
| Concrete Bridge Development Group | TG2: 2002 Guide to testing and monitoring the durability of concrete structures |
| Highways Agency | BA86/04:2004 (with additions 2006)<br>NDT Advice Notes (Design Manual for Roads and Bridges, Vol. 3, Inspection and Maintenance) |
| Institution of Civil Engineers | 2002 Concrete reinforcement Corrosion: ICE Design and Practice |

had assumed that ASR was a technically interesting cause of deterioration to concrete overseas but generally of only academic interest in Britain. ASR deterioration of structures such as Charles Cross car park in Plymouth and the foundations of electricity sub-stations in the South West had previously been considered as rare incidents. ASR at the Marsh Mills viaducts was caused by alkali-rich cement from the nearby Plymstock works used in combination with certain sea-dredged aggregates and aggravated by road deicing salt. Moisture is required for the reaction, which produces an expansive gel which bursts the concrete structure apart, the internal expansion causing a characteristic map cracking effect on the surface.

Discovery of ASR at the Marsh Mills prompted a nationwide examination of other highway structures. Many were found to be in trouble to a greater or lesser degree and several were replaced. As well as Marsh Mills, there were several other reinforced concrete bridges on the 1969/70 vintage, grade-separated A38 highway between Exeter and Plymouth. Measures adopted were to observe and contain the problem with remedial works such as weather shields to extend the working life of the structure until such time as replacements could be built.

Miracle cure? Bold innovation won Hochtief the contract to replace Plymouth's concrete cancer-crippled Marsh Mills viaducts and gave the Highways Agency a design and build bargain at £12.25M. The idea may

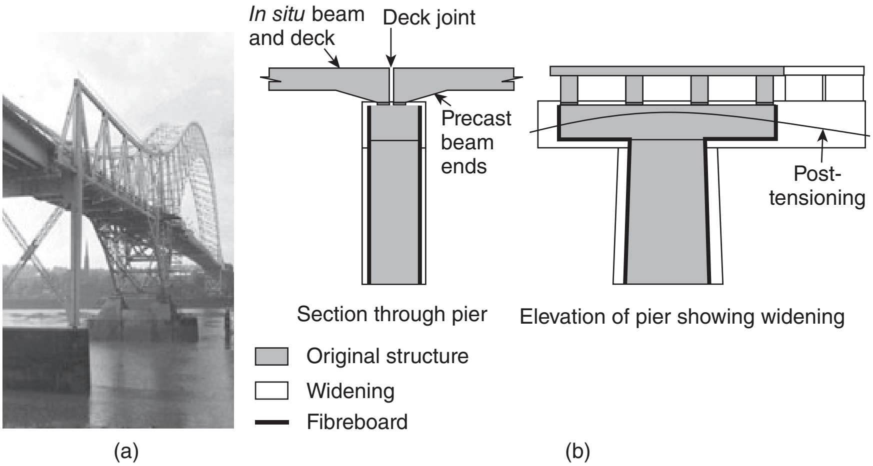



*1.7* 'Miracle cure': the replacement of the 'cancer crippled' Marsh Mills viaducts.[19]

have seemed simple but its execution was nerve wracking. Traffic diversions could be avoided almost entirely by just assembling the new viaduct decks on temporary supports beside the old structures while building the permanent foundations and piers beneath them; traffic was diverted for a few hours while each new viaduct was slewed sideways on to the permanent supports. Slewing in the viaducts probably involved the biggest such bridge jacking operation ever attempted, see Fig. 1.7. Each sliproad deck was some 400 m long and weighed about 5250 tonnes, and was supported on bearings sliding on tracks set on seven or eight intermediate piers. Just for good measure, the viaducts were each set out on a curve with a severe gradient and a crossfall. Motivation for this extreme solution came from the lane licence charges imposed by the Highways Agency. Overnight closure of any two lanes of the A38 would have cost the contractor £5000, at a weekend £18,000 a day and during the week a thumping £25,000 a day. In effect, Hochtief, the contractor for this project, saved these charges and spent money instead on extensive temporary works.

*Silver Jubilee Bridge*

*The Silver Jubilee Bridge, Runcorn, UK*, constructed in the 1960s, is the third largest bridge of its type in the World, see Fig. 1.8(a). It is part of a major highway route in the North West of England and, as such, the structural integrity and durability of this structure is critical. Over the years, the reinforced concrete approach viaducts of this bridge complex suffered from carbonation, chloride attack and alkali–aggregate reaction (ASR). Prob-

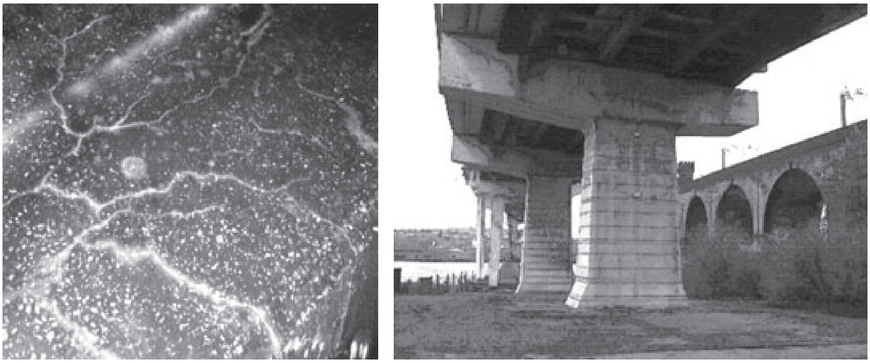



*1.8* Pier encapsulation: (a) the Silver Jubilee bridge, (b) widening by adding a separately supported 5-m-wide strip of deck.[21]

lems on the 34-year-old 27-span crossing with its striking 330-m central lattice steel arch, were first identified in 1989.[20] The three-span bridge itself, with its concrete deck, remained in reasonably good condition thanks to owner Cheshire County Council's £1M a year maintenance programme. But the all-concrete approaches presented a less favourable report. Each is made up of four *in situ* longitudinal deck beams carried generally on a single central pier with integral crosshead.[21]

The ever familiar story of road salts seeping down through leaking deck expansion joints to attack beams, crossheads and piers, was all too evident on both sides of the Mersey River. The worst damage was beneath the Widnes approaches, which had been widened in 1977 by adding a separately supported 5-m wide strip of deck, see Fig. 1.8(b). Problems were caused by a 500-mm-wide longitudinal infill slab, which connected the original and extension sections of the deck. Flexible joints supporting both sides of the infill were leaking, allowing chloride-rich surface water to run down. Chloride levels in the rectangular beam, which was up to 2-m deep, approached 2% by weight of cement. Concrete had spalled and delaminated with the link steel attacked. However, the four layers of densely packed main 50-mm rebar were relatively unscathed.

During the construction of the widened sections, the aggregates used for the concrete encapsulations were susceptible to alkali–aggregate reaction (AAR). Figure 1.9 shows the classic unrestrained map cracking on the surface of concrete that became apparent during the 1980s. A common way of addressing AAR degradation is to control the availability of moisture, since water is fundamental to the development of the reaction. However,



(a) (b)

*1.9* AAR diagnosed on the Silver Jubilee Bridge, Runcorn, UK: (a) unrestrained ASR cracking, (b) electro-osmosis system applied to encapsulated pier with AAR (foreground).[21]

the encapsulation design meant this was not possible since the fibreboard between the old and new piers was completely saturated. In addition, the design of the encapsulation resulted in the inner pier being saturated. This had the benefit of arresting corrosion of the steel in the chloride-contaminated inner pier by reducing the available oxygen. Any attempts to dry the outer pier out might cause corrosion in the inner pier. The development of electrochemical osmosis for concrete provided the possibility of controlling both the AAR in the encapsulated piers and the corrosion risks to the inner pier associated with any attempts to control moisture, see Fig. 1.9(b).

Electrochemical osmosis is a technique that can reduce relative humidity (RH) in concrete by the application of low-voltage direct current (dc) pulses. Below a certain level of humidity, which depends on the concentration of aggressive species, corrosion will not occur. In concrete this has been shown to be 60 to 70% RH. AAR is unlikely to occur at below 85% RH.

The added advantage of electrochemical osmosis is that as the water is forced towards ground rods next to the pier, any chlorides in solution are expected to be drawn out. This then reduces the risk of corrosion, in addition to the lower risk associated with a lower relative humidity. As well as reducing the moisture content, the system is designed to provide a cathodic pulse to the reinforcement. This pulse gives the steel a low level of cathodic protection, thus reducing the risk of corrosion. The system was applied and within weeks of application visual evidence was available that suggested the pier was drying. A drain hole installed in the encapsulation started flowing for the first time since its installation. In addition, the RH as measured using internal probes reduced to the order of 65% and this low humidity was sufficient to prevent further AAR formation and corrosion.

## 1.6 Durability and integrity assessment in the 1990s

It is not surprising, from the above examples, that there was, in the 1990s, an upsurge in activity in durability and integrity assessment, with many results of research funded by UK Research Councils and others published on the topic, including work at University of Liverpool on reinforcement corrosion assessment. Techniques such as linear polarisation resistance to assess *in situ* corrosion rates were under development and evaluation both in Europe and the USA. Work included environmental influences on interpretation.[22] Associated techniques included improved equipment for air and water permeability (work done at Queen's University Belfast) and moisture measurements contributing to efforts to develop lifetime prediction models. Two major areas of integrity assessment were the radar and dynamic response methods.

### 1.6.1 Subsurface radar

The first serious studies of the capabilities of the subsurface radar technique with respect to structural concrete in the UK, appeared in the early 1990s. This was followed by further research and a rapid growth of interest in the topic with many companies offering specialist series of equipment. Further stimulation was provided by a major EU-funded project leading to significant improvements in understanding and computer modelling capabilities. The work at the University of Liverpool included determining the dielectric properties of materials and antenna performance characteristics as well as computer modelling and applications of neural networks. A Concrete Society Technical Report (see Table 1.2) promoted industrial acceptance and this is now well-established. The technique is particularly useful in detecting buried metallic features, changes in moisture conditions, and element thicknesses. Development has continued steadily, with modelling software freely available.[23]

### 1.6.2 Dynamic response testing

Extensive developments of impact–echo testing to identify hidden features including delamination and voids occurred in the USA with equipment developments both in the USA and in Denmark. Apart from some work at Edinburgh, UK activity has been limited, but extension to spectral analysis of surface waves is receiving attention in several countries around the world.

Although work on strength assessment generally declined, applications to lightweight concretes were considered at the University of Liverpool. Interest in early-age assessment also continued with successful use of the

Lok-test on the European Concrete Frame Building Project at Cardington[24] related to fast-track construction in collaboration with Queen's University Belfast. The effects of digital technology on equipment development has been particularly important, leading to significant increases in portability, coupled with major enhancements of data storage and processing capabilities and improved presentation. The use of tomography is attracting interest; in this technique computer algorithms can build up two- or three-dimensional images of buried features, and data fusion techniques for combining results from different tests are currently receiving particular attention in Germany.[25] Waveform analysis for techniques such as radar and dynamic response has also been greatly facilitated leading to improved interpretation capabilities. Acoustic emission has been the focus of attention, both for long-term monitoring and short-term assessment.

Long-term monitoring of near-surface regions has also been considered with a range of embedded sensor systems to assess factors related to reinforcement corrosion, including pH levels, moisture, chloride ingress, half-cell potentials and current flow at different depths below the surface.[26] Abrasion resistance work at Aston has also been extended to fibre-reinforced concrete floors.[27] The value of comparative studies of equipment is recognised by the availability of large-scale outdoor test slabs at BAM in Germany, and by reports on the use of covermeters by a range of operators in Japan.[28] These, together with enhanced use of fibre optics and other techniques, have been reviewed in the latest 4th edition of *Testing of concrete in structures*.[16]

New documentation in the 1990s was extensive including the handbook by Malhotra and Carino,[29] new parts of BS 1881 (see Table 1.1), and CIRIA guides to equipment and early-age *in situ* strength monitoring (see Table 1.2). A compendium of available methods was also published in Germany and the ACI Committee 228 produced an important review report on NDT Methods, which included radar and stress-wave techniques. Another key feature was the establishment of the series of International Conferences on NDT in Civil Engineering. The first was held at Liverpool in 1993 followed by Berlin (1995, 2003), Liverpool (1997), Tokyo (2000), St Louis (2006), and Nantes (2009).

## 1.7 European Standards after 2000

From 2000 to 2004, four European Standards were published to replace the relevant British Standards (see Table 1.3). Although the detailed procedures are broadly similar, the major difference is that in most cases guidance on the number of tests, interpretation and applications is not provided. This could be regarded as a retrograde step although a document on *in situ* strength estimation has recently been published and a national annex is in preparation. Other new European Standards also cover acoustic emission,

*Table 1.3* European Standards

| | | |
|---|---|---|
| BS EN 12504 Testing concrete in structures | | |
| | Part 1: 2000 | Cored specimens – taking, examining and testing in compression |
| | Part 2: 2001 | Non-destructive testing – determination of rebound number |
| | Part 3: 2005 | Determination of pull-out force |
| | Part 4: 2004 | Determination of ultrasonic pulse velocity |
| BS EN 13791 Assessment of *in-situ* compressive strength in structures and precast concrete components | | |

abrasion testing and bond testing of repair materials. Some brief comments on these European Standards may be made.

### 1.7.1 Core testing

*Core testing* procedures are limited to establishing an estimate of *in situ* core strength. There is no specific requirement for soaking before testing, although this is optional and no corrections are provided (including direction of drilling). Procedures are thus considerably more basic than current UK practice.

### 1.7.2 Rebound hammer

Detailed changes in the *rebound hammer* procedure include the minimum number of tests (from 12 to 9) and minimum spacing (20 mm increased to 25 mm) as well as acceptance criteria for a set of readings. If more than 20% of the set are greater than 6 rebound units from the median, the whole set is discarded. Factors that may influence results are listed, but not discussed.

### 1.7.3 Ultrasonic pulse velocity

*Ultrasonic pulse velocity* procedures are essentially unchanged and guidance is given on factors influencing results but no reinforcing steel corrections are provided. Procedures are, however, given for indirect measurements and development of strength correlations.

### 1.7.4 Pull-out testing

*Pull-out testing* includes both cast-in and drilled approaches and seems to be based on the 25-mm diameter Lok/Capo test systems. Procedures are essentially the same as BS1881 Part 207 with guidance on strength correlations and accuracies. Use for formwork stripping applications may be covered by a national annex.

### 1.7.5 *In situ* strength estimation

For *in situ strength estimation*, a new document BS EN 13791:2007 is very detailed and based on cores and indirect methods (as above) calibrated on cores. The effects of number of tests, and *in situ* variations are identified with guidance on planning, sampling and evaluation of results. This document partially replaces the outdated BS6089 (which is being revised as a complementary standard).

## 1.8 Other documentation

Other recent UK documentation is shown in Table 1.2, including the Highways Agency Advice Notes, which include acoustic emission and tomography and provide new focus on contractual processes, including tendering, with a full site trial. Recent documentation from the USA is summarised in Table 1.4 including a new (2003) edition of the ACI strength testing report, and the ACI Report on NDT methods is currently being revised. A major new industrially focused state-of-the-art report has also appeared in France[30] although this is only available in French.

## 1.9 Future developments

Two current RILEM committees are examining acoustic emission, and interpretation of NDT results (with particular emphasis on test combinations). These activities are largely consolidation of knowledge and dissemination to a wider audience. Following reports from recent committees on near-surface durability testing and in-place strength testing, they may help to stimulate interest in the topic amongst engineers. Funding for new research into *in situ* testing is very limited both in the UK and Europe as

*Table 1.4* Selected American reports and standards

| | |
|---|---|
| ACI 228-1R:03 | In-place methods to estimate concrete strength |
| ACI 228-2R:98 | NDT methods for evaluation of concrete in structures |
| ASTM C856 | Petrographic examination of hardened concrete |
| ASTM C876 | Half-cell potential of uncoated reinforcing steel in concrete |
| ASTM C1074 | Estimating concrete strength by the maturity method |
| ASTM C1383 | Measuring the P-wave speed and thickness of concrete plates using the impact–echo method |
| ASTM D6087 | Evaluating asphalt-covered concrete using ground penetrating radar |

this is no longer seen as a priority area, thus future developments are likely to be initiated by equipment manufacturers in response to market needs. Education and training is a key feature here. Coverage in degree courses is patchy and although recent efforts to establish both engineer and technician level training programmes may help to address the issue, increased incentive for industrial uptake is needed. Formal certification is seen as an important feature but costs of training are a restraining factor. The British Institute of NDT has recently established a Civil Engineering specialist interest group, which is a most welcome development.

Future techniques are difficult to predict, but magnetic imaging work on reinforcing steel detection and condition assessment may become more suitable for site use. A growth in the use of tomography is to be expected as interpretation software becomes more readily available at reasonable cost and data fusion of test combinations offers considerable potential. It is also to be expected that techniques for durability monitoring will be applied more widely in new construction whereas pulsed-thermography and dynamic response methods should become more established. Industrial surveys suggest a desire for non-contact scanning to minimise surface preparation, together with improved long-term monitoring systems; new wireless transducers may also have an important role.

## 1.10 General observations and conclusions

Durability performance of concrete structures is unfortunately not always as good as anticipated for a variety of reasons. The principal driving force for the numerous developments of non-destructive test methods and equipment has been the requirement of industry worldwide for long-term maintenance strategies. There have been significant advances in equipment capabilities and a range of new techniques related to durability and integrity assessment. These techniques have become established in practice. The troubleshooting and maintenance role of *in situ* testing remains assured. However, attitudes amongst the engineering community towards in-place testing for quality control during construction remain largely unchanged. This is apart from limited acceptance of testing for strength development monitoring and increased use of covermeters. Cubes/cylinders remain the 'gold standard' for concrete acceptance for the foreseeable future.

Digital technology has greatly enhanced data handling, processing and interpretation capabilities. Prediction accuracies on-site, however, remain largely unchanged in some instances owing to the dominance of practical factors including operator and concrete variability.

Published worldwide research output is almost overwhelming, and continued vigilance is required to avoid effort which is simply 'reinventing the wheel'. Despite the major efforts in producing the British and European Standards outlined in this chapter, there are notable gaps, especially relating to reinforcement corrosion assessment. Consequently, TR60 (see Table 1.2) is relevant here, whereas Table 1.4 lists some American Standards on topics not covered by British Standards.

Although previously perceived needs for improved documentation have largely been addressed, the need for enhanced training opportunities remains. The role of international organisations and national industrial bodies in sustaining dissemination activities is vital for continued development, and bridging the gap between research scientists and engineering practitioners.

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