

Durability of corrosion resisting steels in concrete

K. W. J. Treadaway, R. N. Cox and B. L. Brown

Improving reinforced concrete durability in the Middle East during the period 1960–1985: an analytical review

J. D. Simm and P. G. Fookes

A speaker

In the Middle East one is trying to keep chlorides and sulphates out of constructions, whereas in the industrialized north winter dictates that as much salt as possible should be used. In the past three decades in the industrialized northern nations which suffer from bad winters the use of road salt has increased 15-fold. It would be hard to compare the damage this has caused with that resulting from the use of in-built chlorides in the Middle East.

2. The worst corrosion always occurs at stirrups in bends, the corners of beams and so on. Corrosion may be so severe that a bar may be lost entirely although there may be little corrosion in the straight lengths of the stirrup and none in the main bars. I therefore think research should concentrate on the structural integrity of stirrups rather than the loss of bars.

3. In my experience the most important aspect of long-term deterioration of reinforced concrete is the bond stress of bars. Delamination occurs at the surface and it is the loss of bond rather than the loss of bar which is generally far more damaging in terms of structural integrity. It is amazing how much smaller loss of bar can be accepted because this corrosion is generally random and does not occur in bands. So if the bars in a slab have punctured it is probable that under the cover there is severe pitting corrosion in bars which are not in line with each other. There is therefore not a great loss of section at any particular section, but a complex failure interaction of combined loss of bar and then bond, which is transferred in length, in plan, to the next section. Some strength pick-up results from what is lost in one bar and this is transferred to the next. This sort of problem has become apparent only in the past few years.

4. Epoxy-coated steel is in constant use in America and is mandatory in some British, American and Canadian codes. However, the quality of some American epoxy-coated steel is poor and care is needed when bending it to avoid cracks which would be damaging. Epoxy-coated steel bars are also difficult to cut. It is

DISCUSSION

possible to take a cage of steel and weld it, because the bars are cut and bent, and then to coat the cage by dipping it into a fluidized bed of epoxy.

5. It seems odd to me that with vast reinforced concrete members reinforced at the perimeters and surrounded in cover concrete, it is the cover concrete which gives protection provided it does not crack. Early thermal shrinkage will increase the chance of cracking if the cover is increased. So extra cover may stop general carbonation and chloride attack, but it does mean that there will be more cracks, and cracks are a direct path for chlorides and also for carbonation which finds its way down the side of the cracks. In America it is fairly common to add to concretes a plastic fibre which is cut into very fine elements. When it is added to a mix in proportion it forms very fine plastic hairs—reinforcement elements—which can give a very tough cover. It certainly limits cracking and thermal shrinkage cracking.

6. I think more attention should be paid to early thermal shrinkage cracking and to toughening cover concrete to try to stop cracking. In some of their heavy pours for tunnel work for precast tunnels, the Dutch have pumped iced water into the mix. In the Middle East vacuum concrete is being considered as a means of providing a very low water/cement ratio with a high water/cement ratio for dressing as a means of providing a non-crack cover.

Mr A. Safier, Armand Safier & Partner

Both the Papers have addressed the facts about the materials themselves. However, it is omissions by human beings, including engineers, and not materials which cause failures. The human factor too needs to be addressed.

8. In building, construction materials are normally used in the form they are supplied to the site and fashioned as necessary to fit. The only material which is manufactured on site or in ready-mix works is concrete, the production of which is a highly reactive chemical process.

9. Concrete is used widely and yet the people who mix it and place it on site, including most civil and structural engineers, are generally ignorant about chemistry. British standard codes are usually 10–15 years behind time. Engineers therefore need to keep themselves informed of research and developments as they happen.

10. It is incorrect to rely on current codes as the 'state of the art'. Indeed the foreword to BSI standards contains the warning 'compliance with a British Standard does not of itself confer immunity from legal obligations.' The state of the art is related to what engineers should know, rather than what is reflected in codes.

11. I once appeared in court in a case concerning the failure of a chimney due to physical deformation consequent on temperature and chemical effects. In my report and under cross-examination I said that what went wrong was the result of lack of observance of O level physics. This was accepted by the judge, mentioned in his judgement, and not reversed later in the Court of Appeal nor the House of Lords. Codes cannot repeat all basic knowledge.

12. I would submit that so far as corrosion is concerned all engineers should observe O level chemistry. Nobody should bring chloride in contact with steel and expect the steel not to corrode. I have never permitted the use of chloride in concrete nor experienced any trouble therefrom.

13. As a result of not taking notice of practices in other countries, the UK experienced avoidable problems with high alumina cement. Since 1976 I have been trying to introduce fusion-bonded epoxy-coated reinforcement in the UK, but it is

almost impossible to get it generally accepted. I think that epoxy-coated reinforcement is very economic. However, the fluidized bed method has disadvantages because it does not give as neat, clean and uniform a film of protective epoxy on steel as is achievable by the electrostatic fusion continuous production process.

14. Experiments in the USA^{1,2} on concrete test slabs with non-specification fusion-bonded epoxy-coated reinforcement and reinforcement with many defects in the coating have shown that even under such conditions the coating provides sufficient galvanic insulation to avoid most of the corrosion.

15. I agree that a small number of defects do not matter much as there are usually a substantial number of bars in a reinforced concrete section. It is better by far to put up with a small number of defects, as permitted by ASTM 775,³ than to do nothing and allow corrosion to break out all over.

Dr J. G. M. Wood, *Special Services Division, Mott MacDonald*

The Authors have highlighted that rigorous control of the amount of chlorides in concrete is essential for durability. In design and specification two aspects must be considered: minimization of the initial chlorides and minimization of the rate of chloride ingress to the steel.

17. British standards are a little confusing and need to be more rigorous if simple reliable controls of initial chloride levels are to be applied. BS 882⁴ allows up to 0.06% chloride in the aggregate. For a mix with 1850 kg/m³ aggregate and 300 kg/m³ cement this is 0.37% by weight of cement. BS 12⁵ for cement allows up to 0.1% chloride in the cement. So using British standard OPC cement and British standard aggregate, one could fail at 0.47% chloride to comply with BS 8110⁶ requirements for reinforced concrete with OPC, for which the initial chlorides should not exceed 0.4% weight of cement. For prestressed concrete where the chloride limit is 0.1% the correct control of chlorides from all sources is even more difficult.

18. If the threshold level for corrosion in concrete is about 0.4% of chloride ion by weight of OPC is it prudent when building structures adjacent to salted roads or beside the sea to use up all this buffering capacity at the time of construction? Standards should, like the specifications that have been adopted for current major projects, require that the initial chloride levels from all sources are below 0.06% of cementitious content of concrete where chloride ingress in service is a risk. This requires standards with specific grades of cement and aggregate with appropriate low levels of chlorides. Another anomaly in BS 8110 is that the permitted chloride levels are related to OPC (0.4%) and SRPC (0.2%), which is superficially reasonable as OPC generally has 5–10% C₃A, which binds chlorides, whereas SRPC must have less than 3.5% C₃A. However, OPC can have only 4% C₃A and would have a corrosion threshold of about 0.2% chloride by weight of cement. European cement standards will need to grade cements in bands of C₃A content as do ASTM standards.

19. If concrete is to be made much more resistant to the ingress of chlorides it must be wet-cured. Current British standard curing clauses are too vague and not rigorous enough for concrete exposed to chlorides. Well-cured PFA and slag concretes may resist chloride ingress ten times better than OPC concretes, but they achieve this fully only if they are kept consistently wet for at least 28 days. Improved testing for chloride ingress resistance must be adopted.⁷

20. Where one cannot prevent chloride ingress to the reinforcement, epoxy coating has great potential. However beautifully this is produced in the factory, if

DISCUSSION

it is then bent, cut, rattled along in a wagon and then dumped on site, the damage will negate most of the benefit. New working methods are therefore essential. For tunnel structures Mott MacDonald have been pioneering the introduction of the fluidized bed epoxy coating of cages, after bending and welding, to achieve high integrity coatings for precast segments.⁸

21. Materials cause structural problems because engineers accept materials which are inferior to British standards, which may be written to suit the convenience of suppliers not the needs of customers. For concrete structures to be as durable as the steel, brick and stone structures which have achieved over 120 years' life, the professions must ensure that the results of scientific research and post mortem analysis of premature failures, rather than the dictates of the manufacturers, are incorporated into new European standards and codes.

Mr B. Reeves, Rendel Palmer and Tritton

As Paper 9403 is a review of published data it is limited to projects and research which have been documented. Most papers published concern matters of particular interest and so there will be many instances where information was not available for inclusion in this review. What are not known is the weighting that should be put on the different elements and whether individual firms are traditionally above or below the trend.

23. Once it is appreciated that the penetration of chloride is the prime cause of trouble, the object is clearly to limit the advance of chloride ions in their path towards the reinforcement. Their penetration is influenced by many things which need to be reviewed, thereby generating a balance between the effectiveness of each of these chloride barriers, the protection to reinforcement if epoxy is applied and the quality of the concrete.

Mr P. A. Cox, Consultant

The two Papers clearly demonstrate the importance of limiting chloride in both the mix and by ingress in service. The tests using various steels and coatings also show that benefits to be achieved by such changes are very limited and unlikely to be economic for standard works. The tests on the durability of the steels were made with standard concrete mixes of 1 : 8 and 1 : 6 having water/cement ratios of 0.75 and 0.60 respectively. Although the richer mix gave reasonably satisfactory results this mix is not one that should be used when there is a risk of exposure to chloride and other deleterious chemicals. Work over many years by the Institution of Civil Engineers' Sea Action Committee and others shows that mixes with a water/cement ratio of above 0.45 have limited durability in exposed conditions. Similar comparisons can be made about cement content.

25. Economic pressures have resulted in the use in many locations of concrete of a quality not adequate for its long-term purpose. Much of the deterioration of bridges and other structures now evident could have been avoided by the proper direction of knowledge which has been available for many years. I am concerned that official research such as that reported in Paper 9366 should not continue to encourage the use of inadequate quality concrete in the interest of immediate economy.

Mr L. Collis, F

Why has it taken nearly 30 years to move from a position of broad agreement on chloride limits and an absence of concern about reinforcement corrosion to a

position of universal concern but of considerable disagreement about the limits, despite the fortune that has been spent on corrosion repair and legal costs? Is there a technology transfer problem?

Mr A. L. Gilbertson, *W. S. Atkins Consultants*

I would like to discuss the idea that a problem is first identified, then researched by specialists and finally codified for use by designers. Today's designer works in a no man's land in which he is constantly becoming aware of snippets of information about problems and the research underway. Should he stick to his code of practice or should he be avoiding those problems now by, for example, using FBECR—or is that a potential problem in itself? I believe each designer has to decide for himself and that discussion with his peers helps this process. The Institution of Civil Engineers is an excellent forum for this, but there is a need for much more informal discussion in small groups which could then be reported back to main formal meetings.

Mr J. Barr, *Rendel Palmer and Tritton*

Engineers certainly have a duty to transfer knowledge to operatives on site in a clearly understandable way. Videos are being used increasingly and are very effective. However, I am not sure that in the UK the problem is taken as seriously as it should be. Could the Authors suggest how improvements might be made?

A speaker

I am rather hesitant about putting the passive resistance of epoxy around rebars in concrete and substituting it for the dynamic passivity of steel in concrete. In my view, epoxy as an organic material is very different from concrete that has different structures and I wonder if it is compatible with concrete. Is the idea of epoxy-coated rebars a flash in the pan, rather as epoxy nosing and epoxy waterproof membranes were?

30. I believe there are two major aspects of durability—the problem inside and the problem outside—and that they require different treatment. If the problem is inside perhaps stainless steel reinforcement should be used. If the problem is outside, maybe the UK could learn from Mediterranean countries with hot climates and put a good cover on the outside. In these countries the structural part of the concrete is put up full of honeycombing, with the reinforcement visible. To improve durability a render is put on afterwards. The resultant buildings are very attractive.

31. In my view the key to durability is to understand the passage of water in, around and through concrete because all these problems which arise seem to have water as a root cause.

Dr S. D. Venečanin, *University of Beograd, Yugoslavia*

The Appendix of Paper 9403 lists key words but omits temperature, thermal effects, thermal strains and other words related to temperature. This is surprising in a paper dealing with concrete durability in the Middle East where one of the main causes of damage to concrete is temperature.

33. A specific type of temperature action which damages concrete is thermal incompatibility of concrete components (TICC). Different temperature volume changes in concrete components cause stresses, strains and cracks, so the aggregate of approximately the same coefficient of thermal expansion (CTE) as the CTE

DISCUSSION

of hardened cement paste should be used for concrete which will be exposed to temperature changes in service. Limestones often have a low CTE, which is quite different from the CTE of hardened cement paste. Not one of the 236 references in Paper 9403 deals with the TICC phenomenon.

34. This phenomenon has already been discussed,⁹ since when further work has contributed to the explanation of TICC effects. An explanation of contradictory tests results concerning TICC which have been obtained in the past is attempted in reference 10. These contradictory results are probably one of the main reasons why most authors of textbooks on concrete technology do not pay much attention to the TICC. For example, in reference 10 autogenous healing of concrete is associated for the first time with TICC and experiments are carried out with specimens of young concrete. All necessary conditions for autogenous healing are present in TICC experiments with young concrete; cracks due to the TICC heal easily and often ruin results which could show TICC effects.

35. The cores drilled from the carriageway of a ten-year old concrete bridge could not heal autogenously; tests on such cores have shown distinctive effects of TICC.¹¹ Four of these cores were exposed to temperature changes in a thermal chamber, and four reference cores were kept at room temperature. All eight were then exposed to water pressure tests; 72% more water penetrated the thermally treated cores than the reference ones. The CTE of coarse aggregate limestone in this bridge was about $3 \times 10^{-6}/K$, which is much smaller than the CTE of hardened cement paste. New cracks appeared in the four specimens exposed to cyclic temperature changes, and the permeability of this concrete was higher.

36. Tests at Dhahran University in Saudi Arabia are described in references 12 and 13, and summarized in references 14 and 15. In reference 6 it is concluded that concrete deteriorates significantly in quality when it is exposed to temperature changes: flexural strengths are reduced up to 32%, compressive strengths up to 27%, and permeability increases between fourfold and sixfold. Permeability is studied in reference 15 and fracture toughness is studied as a parameter showing TICC damage of concrete. Probably one of the most important conclusions states that the initial stress in concrete exacerbates the effect of TICC damage. It is also concluded that use of fine and coarse aggregates of different origins (and different CTE) also exacerbates the effects of TICC, as predicted in earlier analytical studies.¹⁶

37. A state of the art on TICC is given in reference 17. The TICC phenomenon should be investigated for all concrete structures which will be exposed to temperature changes, e.g. bridge decks, airport runways and aprons, concrete roads, industrial chimneys and prestressed concrete reactor pressure vessels.

38. The problems of TICC are currently recognized, but much more research work is needed to establish all relevant parameters and definite instructions for practising engineers.

Mr J. R. Stoner, Price Brothers (UK) Ltd

It is apparent that professional opinion among engineers frequently differs sharply from the current provisions of the codes and standards regarding the amount of concrete cover needed for the protection of steel reinforcement in chemically aggressive areas such as coastal sabkhas. Is there a consensus among the Authors as to what constitutes good practice and satisfactory protection, and by what tests or records is this established?

40. Could the Authors indicate the chemical differences between coastal

sabkhas and inland salinas? Is there any difference between salts found in the various deserts of the world or is it reasonable to assume that they are all sulphates or chlorides as in the Gulf and Red Sea regions?

Dr P. B. Hird, *Consulting engineer*

Paper 9403 illustrates the increasing rigour of techniques deemed necessary to produce durable reinforced concrete. Because the design and construction market in the Middle East is very competitive, conflict between economic and technical requirements is liable to be severe. Perhaps a broader view of the problem is needed to ensure implementation of solutions.

42. It appears that reinforced concrete is often used in situations where mass concrete would suffice. Quay wall capping blocks and pipe support plinths seem particularly common examples. Disadvantages of reinforced concrete include the use of expensive techniques to prevent failure, the incidence of failure despite these and the demand for structurally unnecessary repairs. Similar arguments may apply to structural steelwork as opposed to reinforced concrete. In light of this and because the CIRIA guide¹⁸ already exists, guidelines on appropriate design would be more productive than codes of practice. Do the Authors agree?

43. At the design stage of many projects the engineer has insufficient funds for market research, a paucity of detailed local information and there is a distinct possibility that the implementation of specified quality control will be limited. Failures occur at loci where all protective features have broken down. Under these conditions I have favoured a greater number of protective features, built into both design and specification, in preference to concentration on quality assurance on fewer but more stringent features.¹⁹ Can the Authors provide guidance on this?

44. With problems on the scale encountered with concrete in the Middle East, one might expect initial over-cautiousness followed by gradual relaxation as more knowledge becomes available. This has not been the case. Do the Authors consider that there is a danger that trends toward greater stringency generate their own momentum where it would be heresy even to contemplate reducing cover or allowing the chloride content to grow?

Dr D. J. Pollock, *Sir William Halcrow & Partners*

A review of the graphical presentations of papers published suggests that hot weather controls, frequency of testing for chlorides, atmospheric chlorides and the influence of C₃A on corrosion are not increasing. Do the Authors suggest that these topics are less important than those topics where there is an increasing rate of publication?

46. It has been suggested that concrete subjected to saline water appears to be impermeable. Is this not misleading? Some chloride ingress data for a wide variety of water/cement ratios were published in 1985²⁰ and no magic threshold appeared to exist.

Mr V. J. W. Hoad, *Sir William Halcrow & Partners Ltd*

I have noted many examples from observations in Libya and elsewhere in the Middle East in the 1950s to the 1970s which support the conclusions of Paper 9366 about the accommodation of corrosive products and the avoidance of cracking in the case of weaker and poorly compacted concrete. However, corrosion was severe in these cases and eventual collapse of the structures inevitable.

48. With regard to Paper 9403, it seems probable that many engineers using

DISCUSSION

concrete mixes for reinforced concrete work have been very aware of the significance of not incorporating salty constituents into these mixes—there were certainly references to the selection and washing of coarse and fine aggregates in the early 1940s, but in those days the tolerance level to avoid corrosion problems was not known. In the mid 1970s Fookes and Collis^{21–23} helped to quantify allowable limits for chloride in aggregates and mixing water used for reinforced concrete mixes.

49. I have formed the opinion that risks caused by ingress from the atmosphere in the case of well-designed structures made with dense 'chloride-free' concrete mixes are minimal. I would not have the same confidence at and just above the upper splash zone for maritime structures, nor even perhaps in more aggressive environments for other structures. In these regions generally more is required to prevent the ingress of moisture, air and salts towards any steel reinforcement. Wind-blown sea spray and salty sand can also cause problems.

50. The Authors have clearly identified other sources of chloride presence as causes for corrosion. Although wherever and whenever possible designers of maritime works often used to avoid reinforced concrete in their designs it was considered in the late 1970s, and by some it still is, that if good quality concrete is used and normal cover is adopted then a sensible design life for such work can be achieved.

51. I would favour the adoption of 100 mm cover as a compromise in the more critical locations as an important factor and even at the expense of the wider cracks on the concrete surface—these flexural cracks will be no greater at depth than with the more normally adopted cover. Treatment of the reinforcement by fusion-bonded coatings, coating the concrete surface, cathodic protection and admixtures in the concrete will all have to be considered for the more severe conditions and environments.

52. The Authors of Paper 9403 emphasize the difficulties engineers face in determining the proper course of action in the light of the changing state of the art. Would they care to comment on the efficacy of the additives, calcium nitrite and microsilica used separately or together? How would silane treatment of exposed concrete surfaces be rated?

53. It would seem that the ultimate economic mastery of all aspects of reinforced concrete durability in the more aggressive environments may still be some way in the future.

Mr B. N. Sharp, Sir William Halcrow & Partners Ltd

The studies in Paper 9366 are directed to performance with included chloride, as opposed to the ingress of chloride. Nevertheless, as a ten-year study designed to simulate adverse conditions of mix quality and chloride level, the results are surely conclusive as to the performances and limits in the climatic environment of the UK.

55. With regard to the coverage of literature in relation to the state of the art in Paper 9403, it would have been helpful if the 1950s and even earlier had been included. Plotting published references to specific topics may demonstrate an increasing awareness of a problem, but the fewer earlier references do not necessarily demonstrate the converse. In the 1950s the volume of material published on any subject was much less than it is now. In charting a course through the literature, the wisdom of hindsight assumes inordinate proportions. One could all too easily define what now appear to be the best procedures, while ignoring all the

conflicting advice and recommendations to which one was subject over the years. With hindsight certain publications stand out with clarity, not the least of these being the 20th report of the Sea Action Committee of the Institution of Civil Engineers²⁴ which drew on long-term testing begun in 1929. Others, with hindsight, are equally authoritative references but could have led one astray.

56. In § 38 of Paper 9403 the Authors make a cogent statement of the sequence of development of the state of the art. It is interesting how an effective solution can be found, lost and later re-found, the period between being a lost opportunity to progress. This happens particularly when the accent on the application changes. In reviewing the conclusions of all research, one is most frequently struck by the problem of extrapolative judgements on all too short a period of results which can lead to fads and fashions. Time and again the statement is made that tests made with a certain concentration of chloride show no deterioration to date, and even that 'performance is better than in tapwater'. These claims may have little value in the construction industry because the time lag between cause and effect is so long.

57. It must always be borne in mind that a compromise is usually being struck between conflicting parameters, as follows.

- (a) The benefits of higher cement contents have to be balanced against concern for over-rich mixes and the resulting problems in massive sections; hence there are warnings in the German waterfront structures code²⁵ and elsewhere.
- (b) The protection afforded by thicker cover was challenged by the fear of increased flexural crack widths that this would induce. Nevertheless, thicker cover than normal for building structures was clearly enjoined in CP 4²⁶—2 in—and in the German waterfront code²⁵—5 cm. Reduced stresses were enjoined in the latter. ACI 318²⁷ required the minimum cover for cast in place concrete to be 3 in against the earth and 2 in when exposed to weather. The 3 in also allowed for direct placing against soil. British foundation and maritime practice, however, often led to 3 in cover in those days.
- (c) The need for sulphate-resisting cement has conflicting claims. I recall the concern of a resident engineer in 1966 that all Americans were specifying sulphate-resisting cement and who wanted to do the same but was refused. This involved the risk of defying many interpretations of the state of the art as it was viewed at that time.

58. By dealing mainly with the limits for inclusion of salt in the mix, the Authors of Paper 9403 sidestep the more serious problem defined in § 4(d), i.e. the rapid ingress of chloride from external sources.

59. There have been other useful reviews of the history of research and recommendations regarding chloride-associated reinforcement corrosion, in particular that by Pullar-Strecker²⁸ which goes back to the patent for use of calcium chloride in 1885. The Authors' charting of the limits accords closely with both this and my own experience except that limits for the inclusion of chloride ions of about 0.5% were applied in the Middle East from about 1972. A Danish specification for the Middle East limited the chlorides in the aggregates to 750 ppm, i.e. a potential total of 0.3% in the mix by weight of cement. In this case, the cement was specified as sulphate-resisting, and so the limit would most probably have been too high. The Danish designers were opposed to increasing the cover because of the risk of peeling of the surface concrete. Nevertheless, they experienced peeling subsequently.

DISCUSSION

60. In earlier days, much less detail was put into specifications than is the present case, and there was much more scope for discretion and practical striving for good practice in the hands of the resident engineer and the contractor's engineers. Limits and requirements were advised to the supervisory staff, and became approved procedures, which were no less mandatory than the specification document. Absence from the document, therefore, is not necessarily an argument that a practice was not known or imposed at the time.

Mr Simm and Professor Fookes, Paper 9403

Mr Reeves (§ 22) and *Mr Sharp* (§ 55) raised the question of the comprehensiveness of the review and the problem of appropriately rating the data. It was possible to include in our review only data which had been published and which was readily available. However, within these restrictions, the size of the sample of references evaluated is considered to be sufficiently large to provide meaningful results. Mr Sharp expressed interest in the 1950s; despite the title of our Paper, we included a limited number of references from this period. The reason for not including the 1950s within the graphical presentation was partly because, as Mr Sharp states, in the 1950s the volume of material published on any subject was much less than it is now, as can be seen from the fact that we found only six references, but also because this was possibly a less interesting period in the development of thinking. We were well aware of the problem of appropriately weighting the data and the limitations of the histogram method (see § 8 of Paper 9403). In relation to the weighting elements, we are pleased that Mr Sharp agrees with our concept of the significance of certain key publications in influencing engineering opinion, as is seen by the change in chloride levels permitted, described in § 38 of the Paper.

62. In relation to *Dr Pollock's* question (§ 45) on the significance of various topics, we do not agree that those mentioned are less important than those where more papers have been published. In addition, it is inaccurate to state that the interest in hot weather controls, frequency of testing for chlorides, atmospheric chlorides and the influence of C_3A on corrosion did not increase during the period studied. In all cases, whether or not there was sufficient data for a statistically significant trend line to be drawn, inspection clearly indicates that interest is increasing (see Figs 2, 4, 7 and 10 of the Paper).

63. In response to *Dr Venečanin*, we would point out that although the word 'temperature' was not used explicitly, it was included within the general phrase 'Middle East environment'. As stated in § 2 of the Paper, this includes the complex interaction of effects such as temperature, humidity, the prevalence of salt and the quality of the available aggregates created by the Middle East environment (see ref. 1 of the Paper). We agree that considerably more research work is needed before parameters and instructions to practising engineers on the problem of TICC can be properly defined.

64. In relation to Mr Sharp's comments (§ 59) on the application of limits of 0.5% chloride in the Middle East from 1972, we consider that this was not general practice, nor the practice in Mr Sharp's firm, at the time and that the publications which we have reviewed support this judgement from experience. However, Mr Sharp's comments certainly support the view expressed by Mr Reeves (§ 22) that at any one time an individual firm may be ahead or behind the state of the art.

65. On the subject of the individual elements that might be involved in a potential problem of chloride-related corrosion, we agree (§ 30) that it is important to define clearly whether in a particular situation the engineer is dealing with a

problem from without, such as an aggressive salty environment, or a problem from within, where significant chloride levels cannot be eliminated. The comment by Mr Sharp (§ 58) that the ingress of chlorides from external sources is not properly covered is unjustified, both in terms of the text, figures and key words contained in the Paper where the problem without and the problem within are considered with equal interest.

66. The comments of the contributors on the problem without are concentrated on definition of the external environment and methods of resisting the ingress of salts from this environment. The aggressiveness of the environment to which a reinforced concrete structure is subjected, is a function both of its location on the globe (macro-environment) and its location on an individual structure (micro-environment). The range of effects experienced in the marine environment is discussed in ref. 1 of the Paper. We certainly concur with the view of Mr Hoad that the splash zone of a marine structure is the most severe micro-environment (§ 49). Mr Stoner raises an interesting question on the chemical differences of various macro-environments (§ 40). In general, coastal salt accumulations around the world, including the sabkhas of the Middle East, are dominated by the evaporite salts, chloride and sulphate. Inland salt chemistry in the Middle East is usually dominated by sulphates, but elsewhere (e.g. on the South American high plateau) deserts may be dominated by nitrates or even borates; indeed, any evaporite salt can occur locally, depending on the bedrock geology. An important point is that evaporite salts can concentrate in a situation where moisture is lost by evaporation and, therefore, the actual amount of salt present as indicated by the ground soil and water analyses may be much higher in reality when concrete or contaminating aggregates (see ref. 229 of the Paper) are being attacked.

67. On the question of limiting ingress of salts from the environment, Mr Stoner (§ 39) should note that it is generally accepted for aggressive Middle East environments that 100 mm cover should be used, as can be seen from Fig. 15 of the Paper. Apparently, Mr Hoad (§ 51) concurs with this view. The penalty of wider stress induced crack widths alluded to by Mr Hoad (§ 51) and Mr Sharp (§ 57) was discussed in § 35 of the Paper. Providing stress induced crack widths do not exceed the values quoted there, we consider that the benefit of increased cover still pays dividends.

68. However, unless increased concrete cover is combined with other aspects of good materials and workmanship, it becomes invalidated because cracks and pores are generated which allow the ingress of water, oxygen and chlorides to allow the corrosion process to continue (§ 31 refers). Important components here are a low water/cement ratio in the fresh concrete, low permeability, adequate water during curing and, above all, good quality workmanship and site control.

69. In relation to water/cement ratio, it is clear that although, as Dr Pollock (§ 46) states, there is no magic threshold value which ensures that the half cell potential is kept below the critical value of about 350 mV above which chloride-related corrosion is known to occur, it is nevertheless clear that significant reductions in half cell potential generally occur when the water/cement ratio is kept below the value quoted by Mr Cox (§ 24) of 0.45 (see Fig. 1²⁹). Ideally, we recommend water/cement ratios of below 0.42. We agree with comments from other contributors which relate to keeping permeability and thus, ingress of water, low (§§ 30–31); in this respect, wet-cured PFA and slag concretes are very good providing wet curing of them is well done (§ 19).

70. The importance of properly trained operatives should not be underesti-

DISCUSSION

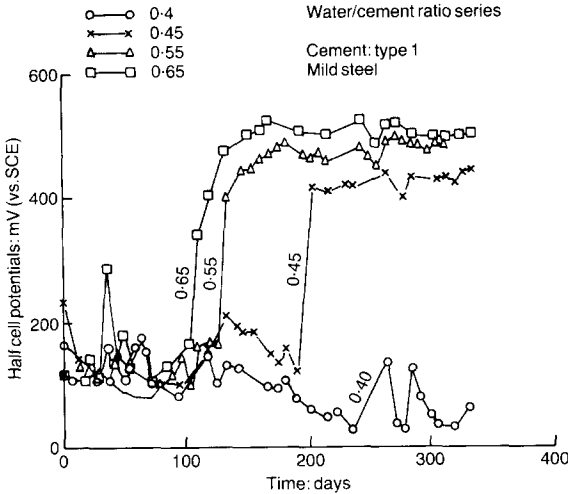


Fig. 1. Potential measurements showing the effect of water/cement ratio

mated. We agree with *Mr Barr* (§ 28) in this respect and consider that in addition to videos, other possibilities for improvement in this area might involve a simple certification scheme for operatives adapted from that commonly used for welders. However, this cannot be a substitute for proper supervision by civil engineers with a full understanding of the processes involved in mixing and curing concrete. In this latter respect, the influence of a good resident engineer can be significant (§ 60). Indeed, some of the better structures created in early years pay a significant tribute to the quality of site control exercised and also to control over the materials selected for inclusion in the concrete. For example, from our own experience some resident engineers in the 1960s and early 1970s, perhaps considered over-zealous at the time, would always exclude aggregates they considered to have too high a salt content, even though the implications for concrete durability of this salt content would not then have been fully understood.

71. If there is no possibility of keeping the chloride levels in fresh concrete below acceptable limits, then the designer essentially has only two options: to abandon the use of reinforcement and to design his structures in mass concrete, or to provide protection to the reinforcement in addition to the protection afforded by the concrete. In response to *Dr Hird* (§ 42) and *Mr Hoard* (§ 50), we would always recommend the designer to consider whether in an aggressive Middle East environment it is possible to create his structure in mass rather than reinforced concrete. This is not always possible and then appropriate coating of the reinforcement must be considered.

72. The engineer must, however, assess his design in an overall fashion and not consider one element of protection out of context with other elements. An appropriate balance of compromise between various measures which may be adopted to protect the concrete and reinforcement must be drawn up in each case. A limited number of well-executed measures with appropriate quality assurance may well prove sufficient, but we sympathize with the practice described by *Dr Hird* in § 43 of adopting a greater number of protective features in situations where site super-

vision and control may be less than desirable. In view of the aggressiveness of Middle East environments, we would counsel against designers and contractors reducing standards from those now achievable. We are not aware of any evidence as yet in response to Dr Hird (§ 44) that reduced stringency could be tolerated. We agree with Mr Hoad (§ 53) that the types and balance of appropriate measures to ensure reinforced concrete durability are not yet fully understood. In relation to his questions in § 52 on the use of calcium nitrate, microsilica and silane, we are aware that little has been published on the results of real situations using these materials. Nitrates as inhibitors are problematical, and are perhaps best used in combination with other preventive measures. Microsilica as an additive is well reported in laboratory and short-term trial studies, and silane, used as a water repellent on concrete surfaces, is also well reported; however, as yet these materials have not stood the test of time.

73. On the question of the interrelationship between engineering codes and publications and the engineer's duty of care, we agree with *Mr Safier* (§ 10) that the state of the art is related to what engineers should know, rather than what is reflected in codes. However, Mr Safier seems unnecessarily harsh on engineers, because many of the developments in concrete technology are hardly simple chemistry (§ 9). What are readily available to the practising engineer are 'codes and other publications from engineering bodies and authorities' (§ 38 of the Paper), as opposed to academic papers on concrete technology which often have no direct application to practice. The engineer's duty of care in taking reasonable steps to keep up to date extends to the former, but not to the latter. In this respect, we sympathize with the view expressed by *Mr Gilbertson* (§ 27). However, the engineering profession could bring more credit to itself by disseminating information on advances on research more rapidly, in a way that allows these advances to be evaluated in the context of general engineering experience and, therefore, applied in an appropriate way.

74. In relation to codes themselves, we support the view of *Dr Wood* that confusions in the present British standards should be resolved to suit the needs of customers, rather than the convenience of suppliers (§ 21). However, as *Mr Collis* (§ 26) suggests, an appropriate level of agreement on the issue of chloride limits has not yet been reached. We suspect that this is partly due to the fact that there is still more to learn, but it may also be because the fortunes which have been spent on corrosion repair and legal costs have established a number of vested interests, each of which may have their own opinions and limited data sets. The technology transfer problem to which he alludes may, therefore, simply be one of persuading these vested interests to talk to one another and reach a compromise.

References

1. SAFIER A. S. Development and use of electrostatic, epoxy-powder-coated reinforcement. *Struct. Engr*, 1989, **67**, No. 6.
2. CLEAR K. C. and VIRMANI Y. P. Corrosion of non-specification epoxy-coated rebars in salty concrete. *Publ. Rds, Wash.*, 1983, **47**, No. 1, June.
3. AMERICAN SOCIETY FOR TESTING AND MATERIALS. *Damage in composite materials*, edited by K. Reifsnider. ASTM, Philadelphia, 1982.
4. BRITISH STANDARDS INSTITUTION. *Aggregates from natural sources for concrete*. BSI, London, 1983, BS 882.
5. BRITISH STANDARDS INSTITUTION. *Portland cements*. BSI, London, 1989, BS 12.
6. BRITISH STANDARDS INSTITUTION. *Structural use of concrete. Part 1: Code of practice for design and construction*. BSI, London, 1985, BS 110.

DISCUSSION

7. WOOD J. G. M. *et al.* Improved testing for chloride ingress resistance of concretes and relation of the results to calculated behaviour. *Proc. 3rd Int. Conf. Deterioration Repair Reinf. Concr. Arabian Gulf*, 1989.
8. ECOB C. R. *et al.* Epoxy coated reinforcement cages in precast concrete segmental tunnel linings—preliminary testing and specification. *Proceedings of conference on fusion bonded epoxy coated reinforcement*. University of Sheffield, 1989.
9. VENEČANIN S. D. Discussion on Some problems of construction aggregates in desert areas, with particular reference to the Arabian peninsula, by P. G. Fookes and I. E. Higginbottom. *Proc. Instn Civ. Engrs*, Part 1, 1981, **70**, Aug., 519–522.
10. VENEČANIN S. D. Experimental study of thermal incompatibility of concrete components. *Proc. 3rd Int. Conf. Durability Bldg Mater. Components, Helsinki*, 1983, **3**, 510–520.
11. VENEČANIN S. D. and KOVAČEVIĆ T. M. Thermal incompatibility of concrete components in concrete bridges. *Proc. 1st Int. Congr. Durability Constr. Mater., Versailles*, 1987, **3**, 1057–1063.
12. MAHAMUD M. M. *Durability and thermal incompatibility of concrete constituents made from local materials in the Arabian Gulf countries*. MSc thesis, King Fahd University of Petroleum and Minerals, 1988.
13. ABOUL-NOUR L. A. *Fracture and permeability characteristics of thermally degraded concrete*. MSc thesis, King Fahd University of Petroleum and Minerals, 1988.
14. AL-TAYYIB A. J. *et al.* The effect of thermal cycling on the durability of concrete made from local materials in the Arabian Gulf countries. *Cem. Concr. Res.*, 1989, **19**, 131–142.
15. BALUCH M. H. *et al.* Concrete degradation due to the thermal incompatibility of its components. *J. Mater. Civ. Engng Am. Soc. Civ. Engrs*, 1989, **1**, No. 3, Aug., 105–118.
16. VENEČANIN S. D. Analysis of thermal stresses in concrete when it is treated as a three-component composite material (in Serbo-Croatian with English summary). *Proc. Symp. Yugoslav Struct. Engrs, Trogir*, 1980, **3**, 97–106.
17. VENEČANIN S. D. Influence of thermal incompatibility of concrete components on durability. *Arabian J. Sci. Engng*, 1986, **11**, No. 2.
18. CONSTRUCTION INDUSTRY RESEARCH AND INFORMATION ASSOCIATION. *The CIRIA guide to concrete construction in the Gulf region*. CIRIA, London, 1984, special publication 31.
19. HIRD P. B. A more flexible specification. *Proc. 2nd Int. Conf. Deterioration Repair Reinf. Concr. Arabian Gulf*, 1987, vol. 1, 633–647.
20. POLLOCK D. J. Concrete durability tests using the Gulf environment. *Proc. 1st Int. Conf. Deterioration Repair Reinf. Concr. Arabian Gulf, London*, 1985, fig. 3.
21. FOOKES P. G. and COLLIS L. Problems in the Middle East. *Concrete*, 1975, **9**, No. 7, 12–17.
22. FOOKES P. G. and COLLIS L. Aggregates and the Middle East. *Concrete*, 1975, **9**, No. 11, 14–19.
23. FOOKES P. G. and COLLIS L. Cracking and the Middle East. *Concrete*, 1976, **10**, No. 2, 14–19.
24. LEA F. M. and WATKINS C. M. *The durability of reinforced concrete in seawater*. HMSO, London, 1960, National Building Studies Research Paper 30.
25. COMMITTEE FOR WATERFRONT STRUCTURES. *Recommendations*, 5th edn. Ernst, Berlin, 1986.
26. BRITISH STANDARDS INSTITUTION. *Foundations*. BSI, London, 1951, CP 4.
27. AMERICAN CONCRETE INSTITUTE. *Building code requirements for reinforced concrete*. ACI, Detroit, 1971.
28. PULLAR-STRECKER P. *Corrosion damaged concrete—assessment and repair*. Construction Industry Research and Information Association/Butterworths, London, 1987, Appendix.
29. RASHEEDUZZAFAR D. *et al.* Towards solving the concrete deterioration problem in the Gulf Region. *Arab. J. Sci. Engng*, 1985, Dec.