Durability of civil engineering structures: annotated bibliography

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Durability of Civil Engineering Structures – Annotated Bibliography

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PREFACE

The Structures Laboratory at the Institute for Research in Construction (IRC) has begun a research program on the durability of civil engineering structures. The aim of this research is to develop techniques for the prediction of service life in design, and for the assessment of residual service life of existing structures for which rehabilitation is contemplated. A review of the literature that was done to identify research needs revealed many hundreds of articles in scientific journals and articles. There are far too many for a designer to read in search of answers for immediate problems, and as a first attempt to make relevant information more accessible, short summaries of selected articles are offered here.

This annotated bibliography was prepared by Dr. Gilbert Grondin while he was seconded to IRC for a year beginning in October, 1992. He is employed by the consulting firm Buckland and Taylor, Ltd. in Vancouver, British Columbia.

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Durability in Civil Engineering Structures – Annotated Bibliography

Introduction

The term durability can be defined as the ability to meet safety, serviceability, and appearance requirements during the required service life. A durable component or assembly must therefore remain safe, fulfill the functions for which it was intended, and maintain an acceptable appearance during a required period of time. This required service life, usually specified by the owner of the structure, is the time during which the structure fulfills all the requirements placed upon it without requiring unforseen costs or disruption for maintenance and repair. The problem of durability of structures has seen a significant increase in popularity in the recent years. As a result of this growing interest in durability, an upsurge of publications on this subject has appeared in the open literature over the past few decades. The growing interest in durability is partly a result of an increasing concern in conservation of resources. In this context designers have to be concerned about several new ideas: 1) using less materials and making the materials last longer which may be achieved by controlling the environment in which the materials are being used; 2) rehabilitation of existing buildings; 3) materials substitution and recycling. We must, on one hand, reduce the amount of waste produced and, on the other hand, find uses for the waste being produced.

Because durability is a vague concept, it is preferable to think in terms of service life of a material, component, or assembly under specific environmental conditions. Experience still plays an important role in the prediction of service life. The past performance of materials or components in various conditions serves as a useful guide to the prediction of service life of similar materials or components in similar environments. However, one cannot rely on experience alone and, when dealing with new materials or conventional materials used in new environments, experience cannot be relied upon. Therefore, techniques for service life prediction need to be developed to assess new materials and different environments.

A review of the literature was conducted to determine the current state of knowledge in the field of durability. The review indicates that a lot of information on durability and deterioration is available, but, unfortunately, most of it is given only in scientific publications. In practice where problems have to be solved now, the designer does not have the time to consult the vast amount of information available in scientific or trade journals. An annotated bibliography has been prepared to make some of this information more easily accessible. This bibliography contains summaries of publications and reports dealing with various aspects of durability. Since abstracts provided with publications are sometimes misleading and do not necessarily reflect the content of the publications, the writer is presenting a short summary which was prepared from a first reading of the papers.

The bibliographic entries have been divided into five areas of interest: case studies, materials, environment, components and assemblies, and service life prediction. The review of case studies is important because experience and reports of investigated failures form the basis of service life prediction of other similar buildings in similar environments and it also helps identify the areas where further research is needed. Since most of the case studies of building failures are causes of litigation, these case studies are usually not published until several years after the investigation. Furthermore, it seems that only a very limited number of field failure cases find their way into the open literature. Studies of field failures provide invaluable information on the quality of design, construction and management of buildings. They also provide data for the assessment of the risk of failure due to design or specification errors and construction errors. However, failure studies do not necessarily give the required feedback of information on performance under normal conditions since failures are often caused by errors or omission in the design. There is a significant lack of reliable data on the in-service performance of materials and components.

Although it is important to be able to predict the future performance of conventional structures with time, it is also important to predict the service life of structures built with new materials or using conventional materials in new environments. Under these conditions past experience does not exist and techniques must be developed to assess the structures. In order to develop tests which can be used to assess the service life of those structures, a thorough knowledge of materials behaviour, the behaviour of components and assemblies, and the environment to which they are exposed is essential. In the following bibliography major sections are addressing those aspects. The final objective of a durability study is to predict the service life of materials, components, or assemblies once the conditions under which they operate have been characterized. For this reason the final section of the bibliography presents papers of various authors discussing various approaches to service life prediction.

Since this review has been undertaken mainly to identify areas where future research efforts should be directed, the number of references on durability of reinforced concrete material and structures has been very limited in this bibliography. The writer feels that a lot of effort is already being directed in this area and the problem is receiving adequate attention. For this reason, this bibliography does not reflect the vast amount of research that has been directed in that area over the past few years. For a more detailed review of the work performed in that area, the reader should consult a State of the Art Report, presented in 1982 as CEB Bulletin No. 148 [1], and the second edition of a design guide prepared by CEB[2].

It is unavoidable that, given the main areas of interest selected in this bibliography, duplication of some of the references shall arise between different sections of the report. In order to keep the size of the report to a minimum, when a reference is repeated only the name of the author(s), the date of publication and the title of the paper have been given in the duplicates. Reference is made in those instances to direct the reader to the section where the complete reference and the summary of the paper can be found.

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1 Comité Euro-International du Béton (1982). **Durability of Concrete Structures – State of the Art Report.** CEB, Paris, Bulletin d'Information No. 148.

2 Comité Euro-International du Béton (1989). **Durable Concrete Structures - Design Guide.** CEB, Paris, reissued in 1992, Thomas Telford.

Case Studies

Case Studies

1. Akers, D.J. (1990). **Evaluation of Reinforced Concrete Masonry in a Highly Corrosive Environment.** *Paul Klieger Symposium on Performance of Concrete,* D. Whiting, Editor, ACI SP-122, pp. 451-467.

The deterioration of a reinforced concrete masonry structure resulted from the change of usage of the building from a general warehouse to chemical storage. The corrosion of the concrete reinforcement was found to be associated to various causes: 1) the walls did not appear to be specifically designed for exposure to an aggressive environment. (no special surface coating was applied onto the absorbent concrete blocks); 2) the cover over the vertical reinforcement varied a lot due to the lack of quality control during construction (in addition, the horizontal steel should have been placed in grouted bond beams rather than placed in the mortar joint where inadequate cover results); 3) the walls were repeatedly exposed to corrosive chemicals due to carelessness when the chemicals were handled; and, 4) the raised tank slab was constructed without end drains thus allowing the spilled chemical to get in contact with the walls.

2. Anon. (1993). **Amoco Building Recladding.** *Masonry Construction,* Vol. 6, No. 4, April p. 150.

This is a follow-up story on J. Trewhitt and J. Tuchman's paper in ENR. The thin marble panels on Amoco Building failed after only 17 years of service. The 1.25 to 1.5 inch panels (44 000 panels) are being replaced by 2-inch thick white granite at the cost of \$60- to \$80- million. As explained in the paper by Trewhitt and Tuchman, the panels started the type of failure consists of excessive bowing of the panels. This expensive recladding job focused attention on the need for conservative design and thorough testing of thin stone exterior panels.

3. Anon. (1980). **Water Leaks Plague Museum.** *Engineering News Record,* Vol. 204, No. 21, May 22, p. 39.

Less than four years after its opening, the Smithsonian Institution's \$31.5 million Air and Space Museum in Washington, D.C., experienced problems of leaking. The building is faced with marble and glass. The area in trouble is on or above grade and the water was believed to bypass flashing or come in through the marble siding. The estimated cost for repair was \$2 million to \$4 million and consisted of plugging leaks and to install insulation where needed. The reason for the needed insulation is not explained and the relation between the needed insulation and the water leaks is not clear.

4. Anon. (1980). **Facades: Errors can be Expensive.** *Engineering News Record,* Vol. 204, No. 5, January 24, pp. 30-32.

The paper reports some cases of building facades failures which have caused, or could have caused serious injury to passerby. The cases reported consist mostly of marble slabs with some brick and stone facades. The cause of failure is reported to be ignorance, carelessness, negligence and greed. One of the cause of the ignorance with respect of building cladding is the lack of research being conducted in that area mostly because cladding does not have all the glamour that the framing and primary structure of the building has. Consequently, engineers receive little or no formation in the area of cladding behaviour and design. The need for a better understanding of cladding behaviour and better quality control during construction of building facades is emphasized. A program of periodic inspection along with proper preventive maintenance is believed to be the key to safer cladding and prevention of costly repairs and replacement of building facades.

5. Anon. (1979). **GAO Decries Bridge Deck Corrosion.** *Engineering News Record,* Vol. 202, No. 5, February 1, p. 11.

According to a report by the General Accounting Office (GAO) nearly one-third of the road bridge decks in the U.S. are seriously deteriorated because of deicing salts corroding the reinforcement. It is estimated that it will cost \$6.6 billion to restore them. GAO identified 162 622 bridges in 32 states with deterioration of deck problem. Many of these decks, built to last 40 years, need repair after 5 to 10 years of operation. Research by the Federal Highway Administration (FHWA) identified four fairly successful methods to protect new concrete bridges from corrosion: membranes with asphalt overlays; epoxy-coated rebars; special concrete admixtures, including dense and latex modified overlays to slow the penetration of salts; internally sealed concrete using wax beads.

6. Anon. (1973). **LBJ Library Needs \$1.8 Million Repair.** *Engineering News Record,* Vol. 191, No. 4, July 26, p. 11.

After two years of operation, the two year old Lyndon Baines Johnson (LBJ) Library at the University of Texas had about 10 percent of its travertine facing panels loose or cracking. Several panels came loose after only about eight months of opening. The panels are held to the reinforced concrete building with Z-type anchors. Although the reports of the investigating engineers were not released, alleged defects in the exterior stone and masonry work cited in the complaint included displacement of slabs, sealant deficiency, stone breakage, mortar that did not meet specifications, and deficiencies in the preparation of the stonework.

7. Arbogast, D. (1990). **Problems Affecting the Service Life of Exterior Sandstone: Case Study, the Burlington, Iowa Free Library.** *Service Life of Rehabilitated Buildings and Other Structures*, ASTM STP 1098, S.J. Kelley and P.C. Marshall, Eds., American Society for Testing and Materials, Philadelphia, pp. 95-104.

The author examines the causes of deterioration, the current condition , and efforts to restore the integrity of a red sandstone facing. The case study consists of the facing of the Burlington Free Library in Iowa. The library was constructed in 1896-1898. Portions of the exterior have suffered deterioration of various sorts (rising damp, spalling, exfoliation, powdering, and efflorescence). Since the time of construction, site drainage and ground water appear to have been major factors in deterioration. In 1971 the building facade was cleaned by sandblasting and a protective coat of clear silicone sealant was applied. The silicone was later found to have trapped natural salts in the surface resulting in swirls of efflorescence. Damaged areas from rising damp were later repaired by trimming back the damaged surface and parging. This shifted the problem of rising damp to the region above the applied parging. Although the sandstone was found to be of good quality with siliceous minerals as a bonding agent, excessive moisture resulted in damage of the building facade. Elimination of the source of rising damp (by altering the drainage pattern on one side of the building) was strongly recommended.

8. Beal, D.L. and R.J. Heywood (1991). **Story Bridge Rehabilitation Study - Concrete Deck Slabs.** In *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design*. Proceedings ACI International Conference, Hong Kong, ACI SP-128, Vol. 1, V.M. Malhotra, Ed., pp. 395-410.

The Story Bridge spans the Brisbane River in Australia. Built in the 1940's, the bridge showed some signs of concrete deterioration. The authors describe the methods used to evaluate the concrete quality, the level and extent of corrosion, and discuss the repair options that were considered for the bridge. The investigation of the bridge was limited to the footways on all sections of the bridge, and the roadway on the steel approach spans. In general, the concrete was found to be of variable quality. The footways, being very thin, were carbonated through their thickness. Poor detailing of the reinforcement had led to zero cover in some critical locations. The asphalt cover on the deck had protected the deck from carbonation.

9. Bjegovic, D., V. Ukraincik, and Z. Beus (1990). **Evaluation and Repair of Concrete Structure in Urban Environment: Case Study.** *Paul Klieger Symposium on Performance of Concrete*, D. Whiting, Ed., ACI SP-122, pp. 427-450.

The authors describe the repair work that was performed on the reinforced concrete structure on the east stand of the FC "Dinamo" stadium in Zagreb. The stand was constructed in early 1960, and 25 years later the bearing capacity was impaired. Visual inspection and laboratory tests revealed that carbonation had taken place and, in the worst areas, had reached such depths that the concrete surrounding the steel had become affected. The concrete cover was found to be very small in most placed and the concrete was excessively porous and segregated in many places. Several mortar compositions were investigated for the repair work, namely, a reference mortar, mortar with added acrylic dispersion, a mortar with added latex dispersion, a mortar with added silica fume, a mortar with added acryl and silica fume, and a mortar with added latex and silica fume. Although all the mortars performed well, the mortar with added silica fume was selected due to its lower cost.

10. Carrier, R.E. and P.D. Cady (1973). **Deterioration of 249 Bridge Decks.** Highway Research Record No. 423, Highway Research Board, pp. 46-57.

A survey of 249 four-year-old bridge decks was performed in the state of Pennsylvania. The objectives of the study were: to discover the extent and nature of deterioration of a large sample of fairly new bridge decks; and to evaluate the relative importance of factors causing deterioration on these decks. Fracture planes and spalls, the most serious form of deterioration from a repair cost standpoint, were found on 22% of the decks. 95% of the decks exhibited surface mortar deterioration, with 97% of the affected area attributed to wear and only 3% attributed to disintegration of weak mortar. A total of 6.7 miles of cracks were encountered on the 21.5 lane-miles of deck surface observed. In essentially every case, the cracks were transverse and occurred directly above the transverse reinforcing bars. A total of 68.7% of the decks exhibited noticeable popouts. Map cracking appeared in 20% of the decks. Insufficient reinforcement cover was detected in nearly all cases where spalls were observed. Although other factors were identified as contributing factors to the decks deterioration, inadequate concrete cover was believed to be the governing factor.

11. Cuoco, D.A. and E.E. Velivasakis (1989). **Aluminum Curtain Wall Panel Failure, Assessment and Repair**. *Durability of Structures*, IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/2, pp. 689-694.

The authors summarize an investigation of the failure of an aluminum curtain wall panel of a high-rise building in New York City. A review of the original design and drawings indicated that the panels were not unusual. A metallurgical investigation of the failed panels indicated that the failure was due to fatigue failure of poorly welded clips. Since the building contains 9000 panels, replacement of all the panels was not practical. The panels were all inspected in the field and the loose panels, indicating failure of some of the clips, and those needing repair were repaired and all the panels were fastened at their base with stainless steel screws. A finite element analysis of a typical panel indicated that the strength of the clips was adequate w.r.t. overload provided the weld was adequate. An inspection program was instated to detect failing panels and implement repairs before the detachment of the panels.

12. Dreger, G. T. (1989). **Cementitious-Cladding Failure - A Building Façade Collapse: An Odyssey of Failure and Lessons Learned.** Building Research and Practice: The Journal of CIB, Vol. 17, No. 6, pp. 337-341.

The author gives a brief presentation of case histories of building facade failures which took place in the past decade. Facade failures have run a close second only to roof failures in overall building systems failures. The author presents a case study of a recent facade failure on the public facility in the tropical climate of Fort Myers, Florida. The Lee County Judicial Complex, completed in 1984 had a facade of painted cement-plaster stucco cladding. The cladding was furred and secured to the masonry and concrete substrate with steel 'Z' channels. The steel fasteners used to hold the vertical Z channels to the concrete blocks and concrete frame were of the same type as those used to fasten steel decks to steel framing. The fasteners were lightly galvanized to prevent corrosion before their installation. Inspection of the fasteners revealed severe corrosion due to the presence of chlorides. The chlorides were believed to come from the atmosphere and the masonry backup.

13. Eldukair, Z.A. and B.M. Ayyub (1991). **Analysis of Recent U.S. Structural and Construction Failures.** ASCE *Journal of Performance of Constructed Facilities,* Vol. 5, No. 1, February, pp. 57-73.

The authors have studied a total of 604 structural and construction failures in the United States during the period of 1975-1986. All the failure cases studied were reported in the Engineering News Record. The failures occurred either during the construction process or during the service life of the project. Over 56% of the failure cases were associated with collapse while 4% and 39% were associated with loss of safety, and loss of serviceability, respectively. Most of the loss of serviceability types of failures were associated with delamination of structural composites, water penetration, and corrosion. The proportion of failures associated to commercial, bridge, and residential projects constituted 48, 21, and 18 percent, respectively. It was estimated that 44% of the failures occurred during the construction process while 56% occurred during the utilization phase. It is also interesting to note that over 86% of the failure cases involved reinforced concrete elements. The study also identified the primary and secondary causes of failure.

14. El-Sayed, H.A., M.G. Abd El-Wahed and A.H. Ali (1987). **Some Aspects of the Corrosion of Reinforcing Steel in Concrete in Marine Atmospheres.** *Durability of Building Materials*, Vol. 5, No. 1, pp. 13-25.

Seven deteriorated reinforced concrete structures exposed to marine environmental conditions in Egypt were inspected. The structural members most affected were ceilings and those less affected were the beams and columns. The corrosion rate was found to vary from 0.06 mm per year to 0.1 mm per year. The main factors responsible for the premature deterioration of the investigated buildings were: 1) poor mix design with low cement content in the concrete; 2) inadequate thickness of the concrete cover; 3) ineffective water-proof membranes on the upper floors; 4) use of ordinary portland cement concrete instead of dense concrete; 5) use of salty water for concrete mixing; 6) use of sand and aggregates contaminated with salts; and 7) susceptibility of the used steel to pitting corrosion that lead to transgranular corrosion cracking when forces are acting.

15. Fischetti, D.C. (1990). **The Montague Building and Watauga Hall: A Comparison of Predicted Service Life Based on Building Materials.** *Service Life of Rehabilitated Buildings and Other Structures*, ASTM STP 1098, American Society for Testing and Materials, pp. 117-124.

The author discusses the renovation of two historic buildings from North Carolina. The two buildings were of similar age, size and construction. The methods used in the renovations were entirely different for the two buildings. The paper discusses the two methods in detail, and which method was more successful in terms of the predicted service life. One of the two buildings was renovated by complete replacement of the existing timber floor system by a two-way flat plate concrete floor system. In the second case, because of tax credit incentives, the existing timber floor system was reinforced with steel plates to meet the code requirements. No prediction of the anticipated service life has been presented. It only seems obvious that the complete replacement of the existing floor system by a reinforced concrete flat plate is more satisfactory on the long run than reinforcing to meet existing building codes.

16. Fookes, P.G., C.D. Comberbach and J. Cann (1983). **Field Investigation of Concrete Structures in South-West England, Part I**, *Concrete*, Vol. 17, No. 3, March, pp. 54-56.

A program of field investigations was carried out on several structures in south-west England in order to help assess causes and types of cracking, their structural significance and remedial measures. The field investigation procedures and the rating system used for the structures is presented. One structure, a multi-storey car park, was chosen for detailed study.

17. Fookes, P.G., C.D. Comberbach and J. Cann (1983). **Field Investigation of Concrete Structures in South-West England, Part II**, *Concrete*, Vol. 17, No. 4, April, pp. 60-65.

Part I of this paper outlined a field classification system for concrete structures, and detailed mapping of members with cracks or other defects. The results of the investigation of a multi-storey car park are presented in this paper. Labour intensive crack mapping of some of the members in the structure was performed. This helped provide evidence to help identify the cause or causes of cracking. Cracking due to alkali-aggregate reaction was identified. The authors concluded that the structures or concretes at greatest potential risk are those retaining fluids or in exposed positions. The design and detailing should therefore pay attention to joints, quick water shedding and efficient weather proofing and limiting passage of moisture across or through the concrete.

18. Frauenhoffer, J. (1992). **Masonry Wall and Window System Leakage Investigation for University Building.** ASCE *Journal of Performance of Constructed Facilities,* Vol. 6, No. 2, May, pp. 107-115.

A two-story reinforced concrete frame building with infill masonry and bands of triple-pane windows developed leakage problems only 10 years after its construction. The windows were leaking and condensation of moisture took place inside the units. An investigation of the building by the author revealed that a lot of moisture got behind the brick cladding and stayed there because of poor drainage resulting from bad flashing detailing. Details such as the use of a brick coping to cap the cavity at the top of the parapet, the absence of effective weep holes, short flashing which were not properly embedded in the backup wall at bolt heads protruded from the shelf angles, and mortar in the cavity were found to be at the source of much of the problems. The seal for the triple glaze windows was found to be inadequate. Recommendations were made to place adequate flashing, replace the brick coping by a conventional aluminum coping flashing, to replace the shelf angles at the top of the windows with stainless steel angles, to place additional control joints, to replace the triple glaze windows with maintainable separate pane units, and to remove the mortar squeeze from the back of the brick veneer.

19. Freyermuth, C.L., P. Klieger, and D.C. Stark (1970). **Durability of Concrete Bridge Decks - A Review of Cooperative Studies.** Highway Research Record No. 328, Highway Research Board, pp. 50-60.

The paper summarizes the results of concrete bridge deck durability studies made by the Portland Cement Association in cooperation with the U.S. Bureau of Public Roads and 10 state highway departments. Condition surveys were made of over 1000 bridge decks. Attention was given to scaling, spalling and cracking. Scaling was not found to be a problem for the bridges surveyed. The observed scaling was found to be related to deficiencies in the air entrainment and inadequate deck drainage. Among the various types of cracking observed, transverse cracking was the form most encountered. Cracks over bars, shallow concrete cover over bars, and permeable concrete allow the de-icing chemical solutions to reach the bars and cause corrosion. Transverse cracking was found to be associated with shrinkage of the concrete. Spalling was found to be the result of corrosion of the top layer of reinforcement as a result of the use of de-icing chemicals. The authors conclude by saying that inadequate construction practice has played a major role in the development of many present durability problems. Examples of shallow cover, ponding of water in gutters, high water-cement ratio pastes at the wearing surface, excessive variation in air content, improper finishing, inadequate curing, and other durability reducing practices have all been observed.

20. Gardner, L.L. and C.A. DeWitt (1992). **Moisture Damage in South Carolina Housing.** *Building Research and Information,* Vol. 20, No. 3, May/June, pp. 166-170.

The results of a survey of 6000 homeowners/occupants in South Carolina indicated that 69 percent of the 1329 respondents complained about moisture problems in their home. It is reported that estimates of annual damages to homes in the United States from moisture and moisture-related insects include over $2 billion in 78-80 and $15.6 billion by the year 2000. The survey conducted by the authors identified several causes of substructure and superstructure problems. All the listed causes of moisture problems are found to be the result of: violation of residential building codes (shallow crawl space with no vapour barrier on the floor of the crawl space); poor workmanship by the builder (no flashing or improperly installed flashing); lack of maintenance of the home; poor or inadequate design details (water draining towards the house).

21. Green, P. (1988). **Structures Need a Low-Sodium Diet.** *Engineering News Record,* Vol. 220, No. 2, March 24, pp. 28-31.

It is estimated that the backlog of corrosion induced distress in bridges would cost the U.S. between $16 billion and $24 billion. However, each year adds another $400 million of deteriorated decks to the backlog. The author discusses the use of cathodic protection as a desirable system for protection of steel reinforcement against corrosion. Although the system has been used extensively on bridge decks, its use is still limited on other parts of bridges. The system consists of placing an inert anode and passing a small low voltage direct current between the external anode and the rebar to charge the steel negatively, making it the cathode. The Federal Highway Administrator has commented the system as the only rehabilitation system that has proven to stop corrosion in salt-contaminated bridge decks. Research programs aimed at developing guidelines to quantify, analyze and repair bridges are briefly discussed. The efforts of individual states at developing and experimenting with cathodic protection are also briefly discussed.

22. Green, P. (1986). **Owners Reclad Damaged Masonry.** *Engineering News Record,* Vol 216, No. 10, March 6, pp. 10-11.

The author discusses problems arising from the use Dow Chemical's mortar additive Sarabond. The additive has been found to leach out chloride ions when in contact with unprotected steel. Many brick building facades had to be replaced because of the accelerated corrosion of the ties embedded in the mortar. It is reported that over 100 building owners had engineers investigate problems related to the use of Sarabond in mortar for building facades.

23. Haver, C.A., D.L. Keeling, S.Somayali, D. Jones, and R.H. Heidersbach (1990). **Corrosion of Reinforcing Steel and Wall Ties in Masonry Systems.** *Masonry: Components to Assemblages,* ASTM STP 1063, J. H. Matthys, Ed., American Society for Testing and Materials, pp. 173-193.

The authors present the results of experimental work on two different masonry walls. The first was a concrete block wall situated near the beach and exposed to sea water. The second was a 12 year old section of veneer wall from the Howe Development Center in Tinley Park, Ill. Both walls were examined for corrosion activity using half cell potential readings, chloride sampling, pH measurements to determine the extent of carbonation in the mortar, and energy dispersive X-ray analysis to determine the composition of the corroded surface. The half cell potential measurements on the beach wall indicated potentials significantly lower than the potential for which there exists a probability of 90% for corrosion. Chloride contents near the rebars (0.45 percent) were significantly over the commonly accepted threshold (0.20 to 0.35 percent). The mortar and grout surrounding the reinforcement was found to be carbonated with a pH of 8.5 to 9.5. Although all the measurements indicated that significant corrosion should have been taking place, very little corrosion was observed in the wall. The veneer wall was inspected because it had to be replaced due to excessive cracking and corroding wall ties. The tests showed only a nominal amount of chloride in the mortar in which corroded galvanized ties was embedded. The pH values ranged from 9.5 near the surface to 10.5 in the center. EDX analysis indicated that the only possible source of corrosion must have been moisture. As a result of their investigation, the authors recommend the use of more resistant wall ties since moisture inside wall cavities and brick facades cannot be avoided.

24. Heidersbach, R. and J. Lloyd (1985). **Corrosion of Metals in Concrete and Masonry Buildings.** *Corrosion/85,* March 25-29, Boston, Massachusetts, paper no. 258.

The authors begin by outlining some actual field cases where problems in buildings have been associated to corrosion of metals. Most of the paper discusses specific problems related to corrosion of metals in concrete and masonry buildings. Control of corrosion is basically done by providing adequate ventilation inside wall cavities, especially near connectors, and providing adequate drainage in order to reduce the time of wetness. The paper does not present any new research but only refers to already published literature. Cathodic protection, an increasingly popular corrosion control technique for highway structures is believed to have only very limited applications in buildings.

25. Heidersbach, R., B. Borgard, and S. Somayaji (1987). **Corrosion of Metal Components in Masonry Buildings.** Proceedings of the Fourth North American Masonry Conference, Los Angeles, California, Aug., paper no. 68.

The first part of this paper is almost identical to the above paper by Heidersbach and Lloyd (1985). Talking about galvanic couples, the authors guard against using galvanized bolts with a stainless steel shelf angle and recommend the use of stainless steel shelf angle and stainless steel bolts in preference of galvanized shelf angle and bolts. The effect of anode to cathode area ratio is not mentioned. In a later section the authors advocate an increase in use of zinc coating and recommend the use of galvanized shelf angles over plain carbon steel shelf angles. It is believed that atmospheric corrosion tests conducted with flat specimens at various exposure sites cannot be used to estimate the corrosion rate of metals inside walls. (The authors do not recognize the potential use of those test results once the nature of the environment inside walls has been defined). Referenced cases of corrosion problems in masonry buildings with metal-stud backup systems are reported. Although stiffer structural design have since been recommended for metal studs to prevent excessive cracking of the facade, the reported cases of metal stud corrosion did not occur on buildings with stiffness problems. Examples are given where galvanized metal studs severely corroded and galvanized masonry ties failed due to corrosion. It is apparent that the most viable way of preventing corrosion related problems is to minimize corrosion by adequate ventilation and drainage. The use of metallic coatings can delay corrosion but cannot prevent it.

26. Hergenroeder, M. (1990). **Long-Term Behavior of Prestressed Girder Slabs in Cattle Stables.** In *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 325-331.

The author reports observations of an investigation of the structural state of prefabricated prestressed girder slabs in cattle stables. Two such slabs collapsed in the early 80's. The collapses were found to be of a brittle nature with no cracking or signs of distress prior to the collapse. Stress corrosion cracking at the areas where insufficient concrete cover existed was found to be the cause of fracture of the susceptible prestressing tendons. Applying Bayes decision theory, the amount of damaged slabs was estimated based on the results from a very limited number of inspections. A greater number of slabs were then investigated using magnetic field measurements to detect wire fractures and infra-red thermography to detect imperfections in the concrete. The results of the statistical analysis where thus confirmed.

27. Hookham, C.J. (1992). **Service Life Prediction of Concrete Structures - Case Histories and Research Needs.** *Concrete International,* Vol. 14, No. 11, pp. 50-53.

The service life prediction of reinforced concrete structures is based partly on experience and mathematical formulation of transport of chlorides and carbonation of the concrete. Although the area has been researched quite well there are still areas where further research is needed in order to obtain better and more reliable predictions of service life. The author presents three case studies where service life prediction was required and existing knowledge was used. In the first case a wharf structure, subjected to the impact of a crane, was deteriorating quite severely under the action of sea salt. In order to allow for long-term plans for the facility the service life had to be determined after repair of the damaged elements was made and protection was provided to reduce the rate of corrosion. The accuracy of current mathematical models was questioned and need for more research to characterize the microclimates identified. The other case studies (which are of a general nature) consisted of a power plant structure and radioactive waste repositories. Future research needs as identified by others are listed.

28. Keller, H., T.W.J. Trestain and A.H.P. Maurenbrecher (1992). **The Durability of Steel Components in Brick Veneer/Steel Stud Wall Systems..** 6th Conference on Building Science and Technology, Toronto, January, pp. 83-104.

The paper presents the results of a field investigation of the durability of metal components in brick veneer/steel stud (BV/SS) exterior walls. A total of eight buildings were inspected using destructive methods. Two buildings each from St-John's Newfoundland, Montreal, Toronto, and Calgary were selected. The wall ties, screws and bottom tracks were found to be the most deficient components of the BV/SS system.

29. Kellermeyer, K.B. and I.R. Chin (1986). **Lessons Learned from Investigations of Over 500 Distressed Masonry and Stone Facades.** *Building Performance: Function, Preservation, and Rehabilitation*, ASTM STP 901, G. Davis, Ed., American Society for Testing and Materials, pp. 152-164.

The authors and their colleagues have investigated over 500 buildings with distressed masonry and stone facades. Although the location of the these buildings is not specified, it is expected that all are from the U.S. The vast majority of the distressed conditions observed in masonry and stone facades occurred as a result of : 1) inadequate provisions within the facade to accommodate volumetric changes of materials; 2) inadequate

provisions within the facade to accommodate differential movements between the facade and the structural frame of the building to which it is attached; 3) improper design and installation of expansion and control joints; 4) inadequate detailing and construction to reduce the entry of water into the facade to acceptable levels and to prevent the entry of water into the interior of the building; 5) the use of wind suction forces in the design lower than the actual wind suction forces.

30. Kudoh, P., A. Hirotani, A. Moriwake, and M. Yasuda (1991). **Evaluation and Rehabilitation of Concrete Structures and Innovations in Design.** Proceedings ACI International Conference, Hong Kong, ACI SP-128, Vol. II, V.M. Malhotra, Ed., pp. 1293-1307.

Extensive repair work was performed on a 12 year old jetty. The cause of damage was chloride ingress. The protective system for the repairs consisted of rebar coating with anti-corrosive material (the exact nature of the material is not mentioned) the use of polymer cement for patching, and the whole deck was painted. The authors report the condition of the repairs five years later. It was found that the surface coating had satisfactorily protected the deck from chloride ingress.

31. Liam, K.C. , S.K. Roy and D.O. Northwood (1992). **Chloride Ingress Measurements and Corrosion Potential Mapping Study of a 24-year-old Reinforced Concrete Jetty Structure in a Tropical Marine Environment.** *Magazine of Concrete Research*, Vol. 44, No. 160, September, pp. 205-215.

A corrosion survey was made of a 24-year old reinforced concrete jetty structure in Woodlands in the northern part of Singapore. The survey of two piles covered the mean tidal zone, the upper tidal zone at 0.8 m above the mean tide level, and the splash zone at 1.3 m above the mean tide level. The chloride content in the concrete increased with height above the mean tide level. The chloride concentration profiles measured at different locations in two piles were in good agreement with those calculated using the diffusion model. The values of the chloride diffusion coefficient D, which were calculated from the chloride profile measurements, ranged from 2.13×10^{-8} cm^2/s at the mean tidal zone to 5.50×10^{-8} cm^2/s at the splash zone. The upper tidal zone and the splash zone, those zones with the highest chloride concentration, were found to be most susceptible to corrosion. The authors discuss in some detail the mechanisms of chloride ingress, the diffusion model, and the chloride corrosion threshold.

32. Litvan, G.G. (1990). **Performance of Parking Garage Decks Constructed with Epoxy Coated Reinforcing Steel.** in *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 421-432.

It has been established that suspended garage decks constructed with epoxy coated steel appear to be prone to excessive cracking. The author summarizes some of the observations made while inspecting some parking garages. Extensive cracking of the slabs has been reported even for a garage built in 1988 where no cars had parked on one of the floors. The author gives an historical review of the use of epoxy coated reinforcing steel. The cause of the excessive cracking is not known. However, it appears to be reasonable to accept the hypothesis that the defect is related to the decreased adhesion between the epoxy-coated steel and the concrete matrix compared to that existing between bare steel and concrete. A protective membrane is recommended to protect the bottom bare steel mat from the chloride and water ingress through the numerous cracks.

33. Litvan, G.G. (1991). **Deterioration of Parking Structures.** In *Durability of Concrete*, Second International Conference, Montreal, Canada, ACI SP-126, Vol. 1, pp. 317-334.

The author makes some observations from a survey performed on 49 parking garages as part of a five year research project. Condition surveys, where they were made, indicate that prior to repairs delaminations in the suspended decks ranged between 0 and 60% in terms of the floor area, the average per garage being 6.9%. Polyurethane has been the most frequently used membrane, comprising 31% of the applications, followed by mastic asphalt and rubberized asphalt 23% and 15%, respectively, latex neoprene 15%, and coal tar epoxy, 5%. In the course of field survey excessive cracking of suspended deck constructed with epoxy-coated rebar was noted in recently built garages. A cause of the excessive cracking is not given. Preliminary results of the survey indicate waterproofing membranes are an effective means to reduce the moisture content in the slab.

34. Litvan, G. and J. Bickley (1987). **Durability of Parking Structures: Analysis of Field Survey.** Concrete Durability -Katharine and Bryant Mather International Conference, SP-100, American Concrete Institute, Vol. 2, pp. 1503-1525.

It is estimated that the cost of repairs of parking garages in Canada exceeds $3 billions. Although the technology required to avoid those problems is available from the bridge construction industry, it is believed that it would be unnecessarily expensive to try to use the same technology for parking garages. In other to try to develop techniques of construction more suitable to parking structures, a survey of parking structures was performed. The authors are reporting some observations for the survey of some 215 structures. It was found that durable parking structures can be built without using exotic methods, and the poor condition of existing structures is mainly attributable to design and construction practice that fall short of those required by the environment. It is estimated that almost all garages built until very recently by conventional methods will require rehabilitation. Repair by patch and waterproof method was found to reduce the rate of deterioration substantially but does not stop deterioration. The use of a waterproof membrane on top of chloride contaminated concrete was not found to cause detrimental effects. No relation was found to exist between extent of delamination and that of cracking, no relation was found between the compressive strength of concrete and the extent of delamination. It was found that the chain drag technique is as good in detecting delamination as half-cell potential measurement.

35. Manning, D.G. (1984). **Accelerated Corrosion in Weathering Steel Bridges,** *Canadian Structural Engineering Conference.*

The paper describes an investigation of the performance of weathering steel in the highway environment where de-icing salts are used extensively in winter maintenance operations. A review of some research projects on corrosion of weathering steel is presented. Based on the review of the literature and field inspection of some 61 bridges in southern Ontario, it is concluded that most of the steel work in weathering steel bridges is performing satisfactorily. Problem areas are locations were debris and moisture can accumulate such as on horizontal surfaces near expansion joints. Blast cleaning was recommended in order to remove the mill scale which retards the formation of the protective patina on the steel surface. Mill scale, because it is cathodic, could lead to pitting of the steel in areas where the mill scale has been damaged.

36. Maurenbrecher, A.H.P. and G.T. Suter (1989). **A Loadbearing Clay Brick Masonry Deterioration Problem: Monitoring of Temperature and Moisture.** 5th Canadian Masonry Symposium, 5-7 June, Vancouver, B.C., pp. 771-779.

The damaged exterior walls of two five-storey apartment buildings were monitored for a period of nine months. The temperature and moisture were monitored on the brick surfaces. The continuous monitoring indicated that both faces of the brick were subjected to freeze-thaw action. The moisture content of the brickwork was found to be strongly influenced by rain. The contribution from air exfiltration was not really noticeable.

37. Morishita, K., Y. Sato, and T. Fuse (1989). **Deterioration Diagnosis and Repair Techniques for NTT Buildings.** in *Quality for Building Users Troughout (sic.) the World,* CIB 89, XI th International Congress, June 19-23, Paris, France, Theme II, Vol. 1, pp. 167-176.

The Nippon Telegraph and Telephone Corporation (NTT) owns approximately 30,000 buildings with some being more than 30 years old. Some of those buildings suffer from deterioration. The paper introduces a method of diagnosing the durability and repair techniques for reinforced concrete buildings. A procedure is outlined which is used by NTT to evaluate the durability of existing buildings. The procedure consists of field surveys to assess the present state of deterioration and then the deterioration progress is assessed. Parameters used to assess the state of deterioration are cracking, depth of carbonation, depth of chlorides penetration, reinforcing bar corrosion, etc. Future deterioration is estimated using the time when a certain proportion of reinforcing steel are corroded. This time is determined by predicting the depth of concrete carbonation and chloride infiltration. Criteria for reinforcing steel corrosion based on experimental results are presented. Deterioration of existing building is evaluated using: infrared inspection to detect exfoliation, gas leakage measurement to detect water leak, and use of sample photographs to evaluate the state of surface deterioration. Some guidelines are given to repair deteriorating buildings. The repairs address only two problems; carbonation of concrete and consideration to restrain it (no method given), and methods to seal cracks.

38. Nanni, A. and W.L. Lista (1988). **Concrete Cracking in Coastal Areas: Problems and Solutions.** *Concrete International,* Vol. 10, No. 12, pp. 67-72.

The authors present case studies of concrete cracking caused by reinforcement corrosion due to a coastal environment in combination with improper workmanship. Identified causes of concrete damage were: 1) lack of adequate cover for both or either of the longitudinal and transverse steel; 2) incorrect selection and installation of balcony parapets (e.g. selection of aluminum for posts embedded in concrete); 3) use of poor quality concrete (e.g. use of sea water contaminated aggregate, use of low strength and high permeability concrete). The proposed repair process is local demolition, cleaning and protection of the reinforcing steel, and patching to sound concrete.

39. Nehil, T. E. (1991). **Rehabilitating Parking Structures with Corrosion-Damaged Button-Headed Post-Tensioning Tendons.** *Concrete International*, Vol. 13, No. 10, pp. 66-73.

 Many of the early long-span concrete parking structures were built using the paper-wrapped button-headed wire post-tensioning system which was brought to the U.S. from Europe. After 10 to 15 years of service, many of these parking structures have been found to be in a deteriorated condition with varying degrees of damage to the post-tensioning system. The author reviews some of the problems experienced with unbonded paper-wrapped button-headed post-tensioning systems in parking garages and presents general guidelines for rehabilitation strategies. Typically, the unbonded prestressing tendons were greased and wrapped in Kraft paper. Corrosion protection was provided only by the concrete. Near the dead end anchorage the wires were unprotected and the concrete cover at the dead anchor could be less than 15 mm. Many other deficiencies are identified at the live anchorage, splices, etc... The lack of internal protection against corrosion in the paper wrapped tendon often requires the installation of some external form of protection against the intrusion of water and chlorides. The author discusses some of the non-destructive techniques of inspecting a parking garage and concludes that the only reliable technique consists of exploratory excavation into the slab at locations most susceptible to corrosion attack. The exploratory work must be conducted very carefully since the prestressing system is unbonded.

40. Page, A. W. (1992). **The Design, Detailing and Construction of Masonry - The Lessons from the Newcastle Earthquake.** *Australian Civil Engineering Transactions*, Vol. CE34, No. 4, pp. 343-353.

 The author presents some observations made on masonry buildings following the December 1989 earthquake in Newcastle, Australia. Many problems were found in masonry buildings mainly because of the poor workmanship and substandard materials. Inspection of many buildings showed that mortar joints were badly executed, poor mortar to brick bond was observed, many buildings had several ties which were not embedded in the brick whyte. In older structures, wall tie corrosion was identified as being a significant factor in the damage incurred to buildings. Corrosion was found to be worst in cavity construction in the mortar joint of the outer whyte of exposed walls. The only effective way of detecting corrosion is to identify the tie location, and remove the appropriate brick in the outer skin to expose the tie.

41. Roper, H. (1989). **Durability Aspects in Maintenance, Repairs and Rehabilitation.** in *Durability of Structures*, IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/2, pp. 651-662.

 The author proposes various definitions for the term durability. The design life of a structure is considered in terms of repair requirements. Investigative procedures are considered and this leads to results of surveys on concrete structures in Australia and suggestions for repair procedures. The author reports that in an Australia wide survey on repair problems, 621 reported cases were related to structural problems, whereas 484 were related to diminution of functional efficiency and surface aesthetics of the structures. Some 590 structures were reported to have been the object of concern to the owner and public, but not to the engineer.

42. Rosenbaum, D.B. and C. Powe (1989). **Dow Wins in Court at Last; Jury Finds its Mortar Additive Sarabond is Safe.** *Engineering News Record*, Vol. 222, No. 20, May 18, pp. 7-8.

 A court decision is presented where Dow Chemical Co. was found not liable for the cracking of building facades on two highrise buildings in Denver. The buildings were built in the early '70s and latter showed signs of corrosion of the anchor bolts for prefabricated brick panels. Sarabond is used to increase the strength of the mortar. It is an organic chloride additive which tends to break down as it weathers, releasing salts. According to published news reports, Dow has paid out roughly $100 million against Sarabond claims. The jury decided that Sarabond makes mortar more corrosive, but at too slow a rate to do damage. The additive was taken off the market in 1982.

43. Sarkar, S. L., S. Chandra and M. Rodhe (1992). **Microstructural Investigation of Natural Deterioration of Building Materials in Gothenburg, Sweden.** *Materials and Structures*, Vol. 25, No. 151, August/September, pp. 429-436.

 Site investigation of some concrete and masonry structures in Gothenburg, Sweden, revealed carbonation to have affected number of concrete structures. The synergistic freeze-thaw action was found to have accelerated the deterioration process in some cases. The masonry structures investigated have undergone a different type of deterioration mechanism. Sulphate efflorescence had affected the brickwork to various degrees resulting in loss of aesthetic beauty to delamination between the brick and the rendering. Water is required for both mechanisms to be activated. The deterioration process and the degradation products were identified using microstructural study.

44. Schupack, M. (1991). **Evaluating Buildings with Unbonded Tendons.** *Concrete International*, Vol. 13, No. 10, pp. 52-57.

The author discusses some of the problems existing with buildings where unbonded tendons have been used. His observations are similar to those of T.E. Nehil (1991). A preliminary evaluation of the condition of the anchorages is done using a vacuum cell on the surface of the concrete at the anchorage zone. This essentially gives an assessment of the porosity of the concrete protecting the anchors.

45. Schupack, M. (1991). **Corrosion Protection for Unbonded Tendons.** *Concrete International*, Vol. 13, No. 2, pp. 51-57.

The author concludes that unfortunate detailing and construction practices of the past have caused a number of problems which have reflected on the ability of unbonded tendons to provide corrosion-free structures. Such factors include but are not limited to: 1) grossly inadequate cover; 2) poor concrete quality; 3) loose sheathing; 4) construction abuse of the tendons; 5) improper filling of the stressing pockets; 6) improper location of stressing anchors; 7) cracking due to inadequate design consideration of structural restraints; and, 8) inadequate drainage.

46. Shoya, M., Y. Tsukinaga, and S. Sugita (1991). **Assessment of Deterioration in Sea-Side Concrete Bridges Located in Cold Regions by In-Situ Tests on the Surface Layer of Concrete.** In *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design*, Proceedings ACI International Conference, Hong Kong, V.M. Malhotra, Ed., Vol. 1, ACI SP-128, pp. 69-83.

The authors describe the results of field investigations on the state and the causes of deterioration in three sea-side concrete bridges located in the most northern district of Japan. Two of the bridges investigated were 14 years old and the third bridge was 52 years old at the time of inspection. The visual damage of the two 14-year old bridges consisted of cracking and some efflorescence. The older bridge showed some scaling and peeling of surface mortar resulting in exposure of the coarse aggregates, longitudinal cracks along the main reinforcement, and efflorescence. In all the three bridges, corrosion of the reinforcing steel resulted in partial loss of cross-sectional area of the rebars and spalling of the cover. The deterioration which resulted in severe pattern cracking was identify to be due to alkali-silica reaction in some members. The authors describe some simple field tests which showed some potential to assess concrete quality.

47. Stockbridge, J.G. (1978). **Evaluation of Terra Cotta on In-Service Structures.** First International Conference on Durability of Building Materials and Components, ASTM STP 691, pp. 218-230.

Although terra cotta is not used very much nowadays on new buildings, it was used extensively as decorative trim and facade cladding in the period 1850 to 1950. As a result, several buildings in use today have a terra cotta facade. The author reports some incidents where failure of terra cotta cladding has lead to loss of life. He also reports on an inspection of 2458 terra cotta clad buildings in Chicago which showed that 45 percent of the buildings inspected had loose and potentially unsafe pieces of terra cotta. The prime causes of those poor conditions were identified to be: built-in problems in the original design of the facades (no drainage path for the water penetrating the cladding, lack of details to allow contraction of the structural frame and expansion of the cladding, lack of expansion joints); infrequent inspections and unqualified inspections, and; need for technical support for qualified inspectors (the author outlines some of the tests developed to assess terra cotta facades in the field and points out that better techniques are required to make the inspections more reliable and efficient).

48. Suter, G.T. and A.H.P. Maurenbrecher (1989). **A Loadbearing Clay Brick Masonry Deterioration Problem: Case Study.** 5th Canadian Masonry Symposium, 5-7 June, Vancouver, B.C., pp. 757-769.

The paper presents the findings of an investigation on a deteriorating exterior loadbearing masonry wall in a building constructed in 1973-74. The deterioration consisted of extensive brick spalling, particularly on the North-East elevation. As a measure of durability, the saturation coefficient (C/B ratio) was determined for bricks obtained from the deteriorated walls. The bricks were found to comply with the 1965 edition of the Standard but not with the 1987 edition. The resulting low freeze-thaw durability is believed to be the cause of the deterioration. The exterior coating applied at an earlier time to reduce the rate of moisture ingress is also believed to have caused an acceleration of the deterioration by slowing down the drying process of the brick. As a remedial measure, exterior insulated cladding was suggested.

49. Tolstoy, N. (1989). **The Design of Field Investigations for Estimating the Extent of Building Failures.** in *Quality for Building Users Troughout (sic.) the World,* CIB 89, XIth International Congress, June 19-23, Theme II, Volume I, pp. 187-196.

The importance of knowing the extent of failure in building elements and materials is outlined. It is from such knowledge that research and development can be directed towards the areas where it is most needed. The author outlines some statistical considerations in the selection of buildings for the survey. It is believed that one of the main difficulties in these investigations is to define what constitutes a failure. Failure has been defined as need for unexpected maintenance. In certain investigations a questionnaire is distributed before inspection. Useful tips on the preparation of such a questionnaire are given and the follow-up inspection are given. Some results of field survey are briefly presently. A survey conducted in 1984 showed that in low-rise housing the sub-structure and mechanical installations were the building elements demanding the greatest expenditure. In high-rise buildings the external walls and windows require the greatest expenditure. Repairs to concrete balconies, replacement of built-up roofing felt, replacement of timber windows and rerender were listed as the most common repair works on high-rise buildings,

50. Tolstoy, N. (1984). **Field Investigations of Moisture in Buildings.** Third International Conference on the Durability of Building Materials and Components, Espoo, Finland, August 12-15, Vol. 2, pp. 422-432.

The author outlines the various causes of water and moisture problems in roofs, walls, and floors of buildings. Recommendations and guidelines are given for the field investigation of buildings showing moisture problems. It is important that a standard procedure be used to investigate such problems in order to avoid the tendency of certain site investigators to always look for the same source of problem since moisture problems can result from several sources.

51. Tolstoy, N., G. Andersson, C. Sjöström, and V. Kucera (1990). **Statistical Field Survey of Exterior Building Materials Degradation.** *Durability of Building Materials and Components,* Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 133-138.

The authors present an investigation of external materials on buildings in the greater Stockholm area. One of the main goals of the investigation was to inspect and account for the observed deterioration of the materials. For roof, windows and walls, an assessment was made of the status of surface finish and underlay. Both were evaluated on a three point scale as either intact, with minor damage, or in need of repair. Record was also made of cause of status and age of material as well as surface treatment. Visual inspection and study of environmental factors such as SO_2 level, proximity to traffic, local pollution sources, proximity to salt water and NO_x formed the basis for the evaluation of the status and causes of deterioration. The surface finish status of wood, metal and rendering was shown to be inferior in areas with heavier sulfur dioxide concentrations. Proximity to salt water revealed no connection with the status of materials (probably because of the small number of buildings in exposed areas inspected). A strong connection was found between the degree of fouling and the SO_2 concentration, the distance from road traffic and the distance from a local pollution source. The maintenance periods were statistically estimated by using the classification of the condition of surface finishes and materials distributed in different age classes.

52. Trewhitt, J. and J. Tuchman (1988). **Amoco May Replace Marble on Chicago Headquarters.** *Engineering News Record,* Vol. 220, No. 12, March 24, pp. 11-12.

Some 43 000 marble panels are used for exterior cladding on the Amoco Building in Chicago. It is estimated that 30% of the panels have bowed between 0.5 in. and 1 in. The rest of the panels have bowed by as much as 0.5 in. or not at all. The panels are 50 x 44 in. and are either 1.25 or 1.50 in. thick and weigh about 275 lb. As a temporary safety measure, the panels are being restrained by stainless steel straps. Investigations are being carried to assess the safety of the panels and to identify possible alternatives for the replacement of the panels. It is estimated that the necessary repairs could cost up to $20 million.

53. Winkler, E.M. (1991). **Weathering of Crystalline Marble at the Field Museum of Natural History, Chicago.** *APT Bulletin, The Journal of Preservation Technology,* Vol. 23, No. 4, pp. 43-47.

The Field Museum of Natural History in Chicago was closely studied for weathering effects, specifically, surface attack by dissolution and cracking of the column ribs. The building was built seventy years ago and is showing signs of deterioration on the surfaces exposed to rain. Loss of marble surface was measured and it was found that the maximum erosion on the ribs of the columns was 3.6 mm on the north side and 4.2 mm on the southwest side. It was found that the faces sheltered from rain, although accessible to dry deposition, had suffered very little deterioration. Photogrammetric techniques were used to measure the difference between the weathered and unweathered stone. Stress analysis of the columns showed that the microcracks observed

on the columns result from the maximum principal stresses caused by the load of the building carried along the axis of the columns.

54. Woodward, R.J. and F.W. Williams (1988). **Collapse of Ynys-y-Gwas Bridge, West Glamorgan.** *Proceedings, Institution of Civil Engineers,* Part 1, Vol. 84, Paper No. 9357, August, pp. 685-669.

The collapse of the Ynys-y-Gwas bridge represents the first collapse of a prestressed concrete highway bridge in the U.K. The bridge had a simply supported segmental post-tensioned deck with a clear span of 18.3 m. The nine internal beams of the deck consisted of eight precast I-sections stressed together both longitudinally and transversely. The cross sections consist of a multiple cell box section with longitudinal joints along the length of the bridge and transverse joint at each segment. The bridge was constructed in 1953 and collapsed in 1985. Although several inspections were performed on the bridge prior to collapse, no sign of trouble was detected. The cause of the bridge collapse was identified as corrosion of the post-tensioning strands due to: lack of an situ slab over the beams, ineffective water proofing, inadequate protection to the tendons resulting from the presence of several joints and improper grouting, opening of the joints between the segments under live load, poor workmanship and the damp environment over the river.

55. Wyman, M.R., T.V. Gumina and J.D. Reins (1990). **Repair of an Improperly Detailed Masonry Facade: A Case History.** In *Serviceability and Durability of Construction Materials*, Proceedings of the First Materials Engineering Congress, Denver, CO., Aug-13-15, Vol. 1, pp. 500-507.

Extensive cracking of a brick facade of a 18 story building took place because of the lack of horizontal joints in the facade. The crushing strength was exceeded due to the weight of the brick and additional stresses induced by restrained expansion. The problem was solved by providing horizontal joints by saw-cutting the brick facade and providing additional shelf angles.

56. Ye, Y. (1989). **Analysis of Structural Failure Events in China.** *Quality for Building Users Troughout (sic.) the World*, CIB 89, XI th International Congress, Paris, France, June 19-23, Theme II: Lifespan of Buildings, Vol. 1, pp. 197-206.

The author discusses the cause of failures of 285 structures in China. Over 83 percent of the failures which resulted in total collapse occurred during construction. The causes of collapse have been identified as foundation failures resulting from errors in design, poor construction quality, unstable conditions existing during construction, poor construction practice such as lack of temporary bracing and early removal of formwork, overload after construction (although this could reflect a deficiency in the codes since the floor of an assembly hall should not collapse under the weight of people), and corrosion failure. Once case of roof collapse due to the corrosion failure of the suspension cables was reported. Although the author discusses only a few cases in particular, it gives the impression that poor design and quality control are at the source of the failures.

Materials

Materials

1. ACI Committee 201 (1985). **Guide to Durable Concrete**, 201.2R-77 (Reaffirmed 1982), ACI Manual of Concrete Practice, American Concrete Institute, Detroit.
   This guide is an update of a previous committee report "Durability of Concrete in Service" which appeared in a 1962 ACI Journal. Separate chapters are devoted to each of the main types of concrete deterioration, namely, freezing and thawing, aggressive chemical exposure, abrasion, corrosion of materials embedded in concrete, and chemical reaction of aggregates. Recommendations are given for conditions where corrosion may be a problem. Among those recommendations we find: use of low permeability concrete, use of adequate steel cover, insure good drainage, limit chlorides in the concrete mix, use of positive protection systems.

2. Akers, D.J. (1990). **Evaluation of Reinforced Concrete Masonry in a Highly Corrosive Environment.** (refer to Case Studies).

3. Allan, J.A. (1992). **Retrofit Ties for Brick Veneer.** *Masonry*, Vol. 31, No. 5, Sept.-Oct. pp. 17-18.
   Typically, distressed masonry walls possess corroded wall ties, ineffective wall ties and/or inadequately spaced wall ties. In order to retrofit masonry walls with deficient ties, a number of repair ties are available. The author briefly presents three different ties which can be used for brick veneer with a masonry wythe backup system and one tie for use with a metal stud backup system. The mechanical rather than the material characteristics of the ties are discussed. The author concludes by saying that most masonry walls showing signs of distress are the result of poor design, poor workmanship and/or a lack of attention to details during original construction.

4. Andrade, C., C. Alonso, J.A. Gonzalez, and J. Rodriguez (1989). **Remaining Service Life of Corroding Structures.** in *Durability of Structures*, IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/1, pp. 359-364.
   The authors present a theoretical study of the loss of strength of reinforced concrete members due to rebar corrosion. The bending, shear, and axial strengths are investigated. The theoretical model is based on a constant rate of rebar corrosion. It is assumed that the corrosion will proceed without damage to the concrete cover, without loss in bond strength, and no loss in steel mechanical properties. No pitting or localized corrosion effects are studied.

5. Arliguie, G. and J. Grandet (1987). **Influence de la Corrosion Atmosphérique des Armatures d'Acier Galvanisé sur leur Comportement dans le Béton.** in *Durability of Construction Materials.* Proceedings of the First International Conference held by RILEM, Versailles, France, Sept. 7-11, pp. 998-1004.
   The zinc on galvanized rebars retards the hydration process of Portland cement. The interaction of the zinc with the cement paste results in the formation of layer of cement paste around the rebar different from the bulk mass. The authors found that prior atmospheric corrosion of the galvanized rebars can minimize the hydration retardation observed with non-corroded rebars. Details of the reaction between the zinc layer (for corroded and non-corroded samples) and the cement paste are given.

6. Ashton, H.E. (1970). **Irradiation Effects on Organic Materials.** Canadian Building Digest 121, National Research Council of Canada, Ottawa, January.
   The author gives a description of the effect of sunlight irradiation on organic materials such as plastics and wood. Although most ultraviolet light emitted by the sun is absorbed by the ozone in the upper atmosphere, the long wavelength UV finds its way to the ground. Since this part of the UV spectrum still has enough energy to break molecular bonds in the long molecule chains of polymers and wood, UV absorption will cause changes to the structure and properties of organic materials. To break the long chains, however, the UV has to be absorbed by the material. Some polymers such as acrylics are transparent to UV and therefore will have good resistance to UV. Others, however, absorb UV or the impurities in the material absorb UV and reverse polymerization taking place (scission of the long polymer chains) result in cross-linking, which in turn results in increase hardness and loss of ductility. In other instances, changes only affect the absorption characteristics of the polymer and yellowing or discoloration can take place. In some cases initial irradiation products are coloured and absorb subsequent UV light, thus preventing deeper penetration. Since only the outer layer is affected, cracking will be restricted to the surface, thus giving rise to crazing.

7. Atteraas, L. and S. Haagenrud (1982). **Atmospheric Corrosion in Norway.** in *Atmospheric Corrosion.* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 873-891.
   Since 1970 a number of programs for field exposure of metals have been initiated in Norway at a number of locations. Bare and surface coated specimens have been studied. In addition to the standard flat plate specimens, specimens of various shapes and wire on bolt specimens have been used. In conjunction with the

field tests, laboratory test programs have been conducted for the investigation of single factors, short-time test program development, and instrument development. The test results obtained from atmospheric exposure test sites are described. It was also found that the corrosion rate of weathering steel was more or less constant after four years of exposure. It was found that short term exposure test results can be very misleading if long-term corrosion must be considered. Correlation of corrosion rate with environmental factors such as duration of precipitation, concentration of SO_2, concentration of strong acid in precipitation and chloride concentration was found to exist. Various regression equations are presented for steel and zinc. Other test programs aimed at studying metal siding, aluminum alloys, and coated steels are also described.

8. Avent, R.R. (1985). **Decay, Weathering and Epoxy Repair of Timber.** *Journal of Structural Engineering*, ASCE, Vol. 111, No. 2, February, paper No. 19510, pp. 328-342.

The paper presents results of research on the decay and weathering effects on epoxy repaired timber structures. An experimental study conducted on two types of weathered joints showed that the epoxy repair responded well. For the southeastern U.S., the deterioration of the glue line was no more severe than the deterioration of the wood itself. It was therefore concluded that the usual precautions in maintenance of exposed wood be used to protect joints which have been epoxy repaired. It was found that decayed joints can be repaired by epoxy injection. However, due to the difficulties of implementing such repairs, it is usually better to replace seriously weathered and decayed timber.

9. Baker, A.J. (1980). **Corrosion of Metal in Wood Products.** *Durability of Building Materials and Components*, ASTM STP 691, American Society for Testing and Materials, pp. 981-993.

The report presents information on the theory of metal corrosion as it relates to the corrosion products and the deterioration of the damp wood in contact with the corroding metal fasteners. New data are also presented on the corrosion of eleven fastener materials in water-borne salt preservative-treated wood. One theory of corrosion of fasteners in wood is that corrosion takes place because of the presence of a differential aeration cell whereby the exposed part of the fastener acts as the cathode due to the higher concentration of oxygen at the surface and the embedded part of the fastener acts as the anode. A condition similar to a crevice corrosion condition sets up and the acidity of the electrolyte around the fastener will increase, thus causing deterioration of the wood around the fastener. If the fasteners are protected cathodically, it has been shown that the alkaline conditions existing around the cathode causes a deterioration of the wood around the fasteners, thus reducing the strength of the joint. A three year test program on nails of various metals in chromated copper arsenate and ammoniacal copper arsenate treated wood showed that copper, silicon bronze, and stainless steel types 304 and 316 nails are suitable for long service life. Aluminum and zinc, tin-cadmium, and cadmium coated steel nails were found unsuitable for long service life.

10. Baker, A.J. (1980). **Corrosion of Metal in Wood Products.** *Durability of Building Materials and Components*, ASTM STP 691, American Society for Testing and Materials, pp. 981-993.

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11. Baker, M.C. (1969). **Decay of Wood.** Canadian Building Digest, Division of Building Research, National Research Council of Canada, CBD 111.

The decay of wood is the result of fungi attack under special conditions of moisture and temperature. The necessary conditions for fungi growth are: a source of infection which transmits the fungi to the wood (contact of sound wood with rotting wood), a suitable substrate to sustain fungus growth (this is the case for untreated wood), moisture (moisture contents between 35 to 50 percent are necessary for fungi to flourish but wood cannot be considered immune until the moisture content is below 20 percent), oxygen, and suitable temperature (although fungi growth is stopped at low temperature, it will resume when the temperature rises again). Acidity is also known to play an important role in the growth of fungi. Two types of rotting, namely, white rot and brown rot are briefly discussed. Five important types of fungi are briefly described. Although control of any one of the essential conditions would be sufficient to prevent fungi growth, control of the moisture content is the easiest in most situations.

12. Barton K. and Czerny M. (1980b). **The Relation Between the Properties of the Medium and the Kinematics of Atmospheric Corrosion of Steel, Zinc, Copper and Aluminum. Assessment of results of first five-year stage in corrosion testing program of the member-nations of the COMECON.** *Protection of Metals*, Vol. 16, pp. 301-308.

    The authors present the results of a five year environment exposure test program on standard specimens of steel, zinc, copper, and aluminum. The test sites were located in Hungary, Bulgaria, Czechoslovakia, and USSR, which encompass unpolluted temperature regions, subtropical regions, and very polluted industrial regions. The test specimens were exposed to the open air and sheltered in louvered cabins. The parameters measured during the course of the investigation were the relative humidity, the temperature, and the cumulative sorption of SO_2 on an alkaline surface. The time-of-wetness was taken as the time at which the relative humidity was at least 80 % while the temperature was above freezing. A regression analysis of the data was performed to determine whether the observed corrosion rates could be explained by the measured parameters. It was found that a good relationship ($r > 0.8$) exists between the corrosion rate and the, time-of-wetness and level of SO_2. The relation was found to apply mainly to steel, zinc, and copper. The corrosion rate of aluminum was not well explained by the measured time-of-wetness and the level of SO_2 . Damage functions are proposed for the metals tested in ambient air and under sheltered conditions.

13. Barton, K., D. Knotkova, P. Strekalov, V. Kemhadze, V. Kozhukharov, A. Sobor, M. Zaydel, and T. Bestek (1980). **Atmospheric Corrosion of Metallic Systems II. Analysis of the Corrosion Aggressiveness of the Media at the Atmospheric Testing Stations of Member-Nations of COMECON, According to the Results of Five-Year Tests on Steel, Zinc, Copper, and Aluminum,** UDC 620.193.2, pp. 323-329.

    The authors discuss the results of five-year atmospheric corrosion tests on steel, zinc, copper, and aluminum, in rural, industrial, and coastal atmospheres. They consider the feasibility of quantitative classification of the corrosive aggressiveness of the atmosphere on the basis of the total duration of wetting of the metallic surface, the contamination of the air by corrosive aggressive components, and a combined factor equal to the product of the annual duration of wetting and the concentration of sulfur dioxide and chlorides in the air. The measurements taken at each site are listed differently than in the previous paper. Namely, air temperature, relative humidity, amount of liquid precipitation, depth of snow cover, duration of fog, duration of wetting of metal surface (with the aid of an Fe-Cu galvanic sensor), wind speed and direction, sulfur dioxide content of air, amount of incident chloride particles over a two month period, and amount of dust pollution. Corrosion tests were conducted both in the open air and in a louvered cabin. The corrosiveness of the atmosphere in the louvered cabin was found to be lower than in the open air. It was also found that as the aggressiveness of the external atmosphere decreases, the level of aggressiveness of the medium in a semi-enclosed atmosphere also decreases but much more sharply than in the open air, although there are exceptions to this rule. In particular, aluminum corroded more rapidly in the louvered cabin than in the open air.

14. Bazant, Z.P. (1979). **Physical Model for Steel Corrosion in Concrete Sea Structures - Theory.** *Journal of the Structural Division*, Proceedings of the ASCE, Vol. 105, No. ST6, June, pp. 1137-1153.

    The author presents a mathematical formulation of the corrosion process in concrete. After outlining the chemical reactions involved, he formulates the transport of oxygen and chloride ions through the concrete cover, the mass sinks and sources of oxygen, ferrous hydroxide, and hydrated red rust due to chemical reactions, the depassivation of steel due to critical chloride ion concentration, the cathodic and anodic electric potential with the concentration polarization of electrodes, and the flow of electric current through the electrolyte in the pores of the concrete. Finally, a complete formulation in the form of an initial-boundary-value problem is obtained. Some of the limitations of the formulation are: 1) the depassivation results from the presence of chloride and not from a reduction in pH (the chloride concentration must reach a threshold value); 2) the corrosion processes on the microscopic scale leading to the formation of corrosion pits are not considered; 3) the formation of red rust only is considered (this is the most voluminous corrosion product and is produced in the presence of oxygen, while black rust has half the volume and is formed in the absence of oxygen); 4) the concrete is submerged in sea water.

15. Bazant, Z.P. (1979). **Physical Model for Steel Corrosion in Concrete Sea Structures - Application.** *Journal of the Structural Division*, Proceedings of the ASCE, Vol. 105, No. ST6, June, pp. 1155-1166.

    The theoretical physical model developed in the previous paper is applied to a simplified calculation of corrosion rates and times of corrosion cracking of concrete cover. Approximate estimates are made of the resistance of the corrosion cell, oxygen and chloride ion transport (assumed to be quasistationary and one-dimensional), time of steel depassivation by chloride ions, and cover cracking due to rust expansion. The model is not evaluated by comparison with test data. Nevertheless, the model shows that the diffusivity of chloride ions and oxygen mainly at the cathodic areas is usually the controlling factor.

16. Beasley, K.J. (1988). **Use and Misuse of Exterior Travertine Cladding.** ASCE *Journal of Performance of Constructed Facilities*, Vol. 2, No. 4, November, pp. 242-253.

Travertine is a type of limestone consisting primarily of calcium carbonate deposited from solutions. It is characterized by its white to brown natural color and random holes and veins. The author discusses various causes of failure of travertine used as exterior cladding. Travertine being a sedimentary rock, it contains bedding planes. The bedding planes create sources of weakness in tension normal to the bedding plane. The major causes of failure are: tension perpendicular to the bedding planes, freezing of water in the pores, the use of epoxy to fill voids (epoxy has a coefficient of thermal expansion much higher than travertine), severe thermal exposure, and corroding of steel anchors. The author identifies corrosion of mild steel anchors and reinforcement as the most common cause of serious stone distress. The use of stainless steel anchors and shelf angles is strongly recommended, along with proper joint and drainage design, to achieve a durable exterior cladding.

17. Berke, N.S. (1991). **Corrosion Inhibitors in Concrete.** *Concrete International*, Vol. 13, No. 7, July, pp. 24-27.

The author presents a brief review of the studies done in the area of concrete inhibitors prior to 1980. The problem with some inhibitors is that they adversely affect the properties of the concrete. Calcium nitrite is used commercially on a wide scale and is not detrimental to concrete properties. Studies performed in the 1970's showed that the mechanism of corrosion protection was that of anodic inhibition. Further research showed that nitrite modifies the oxide film on the reinforcing bar to be more protective than the film that naturally occurs in concrete. Studies have also shown that calcium nitrite might decrease the resistivity of concrete. However, long-term corrosion data show that, in spite of the decrease in resistivity, corrosion rates are significantly reduced.

18. Berke, N.S., D.W. Pfeifer and T.G. Weil (1988). **Protection Against Chloride-Induced Corrosion.** *Concrete International*, Vol. 10, No. 12, pp. 45-55.

The authors believe that quality concrete alone is not sufficient to allow a structure to meet its design life in the presence of chlorides. The use of microsilica and calcium nitrite is advocated. Microsilica reduces the permeability of the concrete, considerably slowing the ingress of water-borne chlorides. Calcium nitrite, a corrosion inhibitor, promotes the stabilization of the steel passive layer, thereby controlling the corrosion rate. The authors show the beneficial effect of microsilica in slowing down the ingress of chlorides. A life cycle cost analysis has shown that the use of microsilica and calcium nitrite in severe environments is cost effective.

19. Bhattacharjee, S., N. Roy, A. K. Dey, and M. K. Banerjee (1993). **Statistical Appraisal of the Atmospheric Corrosion of Mild Steel.** *Corrosion Science*, Vol. 34, No. 4, pp. 573-581.

Regression analysis of exposure data at 17 test sites throughout India lead to the development of 17 different damage functions for steel. Not enough information is presented to be able to construct the damage functions since the units for the factors measured are not given. The authors state that damage functions obtained from exposure tests are site specific and cannot be used for sites with climatological conditions different than those for which the function was derived. The factors specifically investigated were the temperature, the relative humidity, rain fall, the number of rainy days, sulfur concentration in air, and chloride concentration in air. Among those factors, the level of sulfur dioxide, and the concentration of chlorides were found to be the most significant parameters. The effect of relative humidity was found to be not significant at all but one site. At three different sites none of the measured parameters were found to be significant.

20. Bier, TH.A., J. Kropp, and H.K. Hilsdorf (1987). **Carbonation and Realkalinization of Concrete and Hydrated Cement Paste.** in *Durability of Construction Materials*, Proceedings of the First International Conference held by RILEM, Versailles, France, Sept. 7-11, pp. 927-934.

The authors have found that the pore structure of the cement paste is strongly influenced by the duration of curing. A coarse pore structure causes a higher depth of carbonation than a dense structure which is reached after a prolonged curing period. Carbonation alters the pore structure by transforming the calcium hydroxide and the CSH-gel into calcium carbonate. The application of a mortar layer on carbonated surface zones of mortars and concretes was found to restore a high alkalinity in the carbonated matrix.

21. Biestek, T. (1982). **Testing Electrodeposited Coatings in Tropical China.** in *Atmospheric Corrosion*, W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 775-785.

The author presents a brief review of the previous work performed on atmospheric corrosion of electrodeposited coatings in tropical countries. The results of corrosion tests at various exposure sites in China are summarized. The results of those tests were the basis for the Polish National Standard on electrodeposited and conversion coatings for articles exposed to tropical conditions. Test sites at Canton University, Canton Electrochemical Institute, Shanghai, and Julin, Hainan Island are described. The performance of zinc, cadmium, zinc chromated, cadmium chromated, nickel, brass-nickel, and copper-nickel-chromium is reported.

22. Binda, L. and G. Baronio (1984). **Measurement of the Resistance to Deterioration of Old and New Bricks by Means of Accelerated Aging Tests.** *Durability of Building Materials*, Vol. 2, No. 2, pp. 139-154.

During restoration of a building some of the original bricks may have to be replaced by new ones. The compatibility of these new elements with the remaining ones is of prime interest for the structural integrity of the building facade. The authors present a technique used to characterize the original brick and the new one using accelerated tests. Freeze-thaw and salt crystallization tests were used as accelerated aging tests. The degree of alteration was characterized by the loss of compressive strength. The measurement of ultrasonic pulse velocity in bricks was found to be an adequate technique to characterize them in terms of their durability to a detrimental environment.

23. Bjegovic, D., V. Ukraincik, and Z. Beus (1990). **Evaluation and Repair of Concrete Structure in Urban Environment: Case Study.** (refer to Case Studies)

24. Boucherit, N., A. Hugot-Le Goff and S. Joiret (1992). **Influence of Ni, Mo, and Cr on Pitting Corrosion Steels Studied by Raman Spectroscopy.** *Corrosion*, Vol. 48, No. 7, pp. 569-579.

Through the use of Raman Spectroscopy the authors have tried to explain the role of Ni, Mo, and Cr on pitting corrosion of steels. It was found that Ni does not intervene against pitting corrosion (no difference was found between Fe-18Cr and AISI 302). The role of Cr in reducing the pitting rate was found to be its ability to stabilize a particular form of green rust which does not integrate chloride and hinders the Cl^- ingress at the surface. Chromium plays its role mostly at the film/electrolyte interface once pitting has been initiated. The part played by Mo is to protect the metal source and to limit its roughening by the growth of a molybdate layer at the metal/film interface. Mo and Cr act in synergy.

25. Branca, C., R. Fratesi, G. Moriconi, and S. Simoncini (1992). **Influence of Fly Ash on Concrete Carbonation and Rebar Corrosion.** in *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, Proceedings, Fourth International Conference, Istanbul, Turkey, May, V.M. Malhotra, Ed., ACI SP132, Vol. 1, pp. 245-255.

The effect of fly ash addition, either with or without a cement reduction, on the carbonation of concrete was investigated. The results of an experimental investigation indicated that fly ash addition reduces the carbonation rate when used without cement reduction, whereas it accelerates the process when used to replace cement. This is explained by the fact that fly ash possesses a lower content of calcium hydroxide than portland cement. Potential measurements of embedded rebar in the test samples indicated that every process which can reduce the concrete alkalinity is a necessary condition but not a sufficient one to promote corrosion of reinforcing steel.

26. Brillas, E., J.M. Costa and M. Vilarrasa (1990). **Effect of Exposure Time on the Atmospheric Corrosion of Steel.** in *Innovation and Technology Transfer for Corrosion Control.* 11th International Corrosion Congress, Florence, Italy, April 2-6, Vol. 2, pp. 2.79-2.86.

The authors report the results of exposure tests on steel specimens at various test sites in Spain. Generally, the corrosion rate was found to be greater on the surface of the specimens towards the ground which is sheltered from the cleaning action of the rain. Corrosion was found to progress more rapidly during the first year of exposure and then decreased with time. It was found that the weight loss of the specimens could be expressed by the bi-logarithmic law $W=kt^n$, where n was found to be fairly constant between sites but k was found to vary significantly from site to site. The factor k was therefore correlated to the site conditions in term of SO_2 and Cl^- concentration. Using regression analysis, the weight loss expression applicable to all the sites was found to be $W=[(177 + 1.39\ (SO_2) + 2.95\ (Cl^-)]\ t^{0.64}$.

27. Brown, P.W. and L.W. Masters (1982). **Factors Affecting the Corrosion of Metals in the Atmosphere.** in *Atmospheric Corrosion,* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 31-49.

The authors present a discussion of the corrosivity of various atmospheric agents. The agents discussed are: solar radiation and wind (affect the time-of-wetness); temperature which also can affect the time-of-wetness but which effect on corrosion is not yet clear; moisture which is affected by the relative humidity, the composition of the metal, the presence of contaminants, and the presence of corrosion products; air pollutants such as sulfur oxides (with SO_2 and SO_3 the most important), hydrogen sulfide (not corrosive to ferrous metals at concentrations normally found in the atmosphere), oxides of nitrogen (nitric oxide, NO, and nitrogen dioxide, NO_2, being the most important w.r.t. corrosion), and aerosols. The paper is a good source of reference on factors affecting atmospheric corrosion.

28. Building Research Association of New Zealand (1985). **Glazing Plastics - 1. Types and Durability.** Building Information Bulletin 241.

There are four main types of plastic used for glazing: acrylic, glass fiber reinforced polyester (GRP), polycarbonate (plexi-glass), and PVC. Plastics are lighter, tougher, and easier to colour than glass, but they are less resistant to fire, they don't remain transparent, they have more thermal movement, usually cost more initially and are easily scratched. The four main types of glazing plastics are described and their modes of deterioration are presented. The main problems related to the durability of glazing plastics are: loss of surface quality caused by scratching, microcracking or crazing, pitting, surface erosion, chalking; discoloration of the resin; change of the colour of the pigments. Exposure to UV and oxygen causes a deterioration of the mechanical properties of plastics. Surface coatings such as polyvinyl fluoride or acrylic can extend the service life of glazing plastics. Guidelines for cleaning plastics are given. Water dripping from the troughs in corrugated plastic roofing can cause rust spot corrosion on unpainted galvanized steel directly below and, therefore, details which allow drainage of plastic roofing on to unpainted galvanized steel should be avoided.

29. Building Research Association of New Zealand (1985). **Glazing Plastics - 2. Design and Fixing.** Building Information Bulletin 242.

This information bulletin gives some basic guidelines for the proper installation of glazing plastics to avoid premature durability problems. Glass fiber reinforced polyester and PVC are the two plastics discussed in the bulletin. Guidance on the bending radius is given for bending of plastics to avoid stress crazing. Cutting slots of square cornered holes or nicks and notches should be avoided since cracks readily propagate from such stress raisers. Special consideration must be given to accommodate thermal expansion since the thermal movement of glazing plastics is up to nine times that of glass. The use of sealant and tape on plastics should be reduced to a minimum since sealants and glazing plastics are both based on organic polymers and there is potential for interaction between them which could be deleterious to the performance of the plastic. Some sealants may cause surface marring or crazing of the plastic and their use should be avoided when the glazing plastic is subjected to long-term stress.

30. Building Research Association of New Zealand (1984). **Corrosion and Staining of Glass Windows.** Building Information Bulletin 236.

Water is responsible for most of the deterioration observed in window glass. When water comes into contact with glass, sodium atoms near the surface of the glass can interchange with hydrogen atoms in the water. This leaves the surface layers rich in calcium atoms, as calcium is more firmly fixed in the glass structure. This calcium rich surface layer can react with carbon dioxide from the atmosphere to form insoluble residues on the glass. As a result of this reaction the water and the glass surface become alkaline and if the water remains in contact with the glass, the degree of alkalinity will cause further breakdown of the glass. If wetting of the glass surface is non-uniform, corrosion of the glass surface becomes noticeable. The bulletin lists a few techniques to prevent corrosion and staining and guidance for maintenance.

31. Building Research Association of New Zealand (1979). **Use of Anodised Aluminium.** Building Information Bulletin 213.

Anodising of aluminum is performed by passing an electric current through the aluminum while it is immersed in a suitable bath. This produces a considerable thickening of the protective oxide film. The film consists of a dense thin film above which is a tough relatively thick porous film. Use of this porous film is made to colour the surface. The pores of the surface layer can be closed by chemical sealing. The anodized aluminum can be attacked by strongly alkaline or strongly acidic chemicals and, localized attack can occur where the film has been damaged. Guidelines for design and installation practices for good service behaviour are given.

Materials

32. Building Research Establishment (1989). **Wet Rots: Recognition and Control.** BRE Digest 345, June.

    Although both wet rot and dry rot can occur together, the type of rot depends on the conditions in the building. The same basic principles govern the successful eradication of both types of rot but additional measures are necessary with dry rot because of its ability to grow through masonry. The digest describes the main types of wet rot likely to be encountered in buildings, describes how to distinguish them from dry rot, and presents a strategy for their control.

33. Building Research Establishment (1986). **Zinc Coated Steel.** BRE Digest 305, January.

    This digest presents some of the corrosion characteristics of zinc and steel. Zinc will form a stable protective film in environments with a pH between 6 to 12.5, with a low chloride and low oxygen content. Zinc provides protection to steel in two distinct ways. If the zinc coating is continuous over the surface it provides a barrier between the steel and the corrosive environment. The corrosion rate of zinc, once its protective oxide layer has formed, is relatively low compared to that of steel. If the zinc coating is damaged and the steel substrate is exposed, zinc will provide galvanic protection by acting as a sacrificial anode. Zinc coatings can be applied to steel either by hot dip galvanizing, electrodeposition, metal spraying, or sherardising. Curves are presented which gives typical life of zinc as a function of coating thickness in various environments. Finally, corrosion of zinc in contact with various building materials is discussed.

34. Building Research Establishment (1985). **Corrosion of Metals by Wood.** BRE Digest 301, September.

    Wood and metals are used together in numerous applications in construction. Several factors can affect the rate of corrosion of metals in contact with wood. In this digest the factors are identified as moisture, choice of timber species, impregnation with salts, type of metal, the use of wood preservatives, flame retardants and exposure conditions in buildings. Moisture is identified as the most important factor causing corrosion of metals in wood. The threshold value of the moisture content of wood below which no appreciable corrosion of embedded metal occurs is about 20%. Most timbers are acidic and, as such provide a corrosive atmosphere for embedded metals. Many softwood species are less aggressive than many hardwoods. Impregnation by salts (sea water or some wood preservatives and fire retardants) create better electrolyte which helps speed up the corrosion process. Moisture control is recommended as the most efficient way to prevent corrosion of metals embedded in wood and, incidentally, rotting of the wood. Contact between dissimilar metals in wood is also to be avoided since a corrosion cell would be set up whereby the least corrosion resistant metal would suffer from accelerated corrosion.

35. Building Research Establishment (1985). **Dry Rot: Its Recognition and Control.** BRE Digest 299, July.

    Dry rot refers to wood decay caused by the fungus *Serpula lacrymans*. Since dry rot remedial treatment requires elaborate and expensive control measures, its positive identification is important. As opposed to wet rot, dry rot can grow through masonry and may therefore require more elaborate procedures to eradicate the problem. The visual appearance of wood affected by dry rot cannot be used for positive identification. However, the appearance of the fungus is described. Growth of Serpula lacrymans takes place in unsaturated wood with a moisture content above 30%. In well designed and ventilated buildings the moisture content of timber remains below 20%. The primary measure to prevent dry rot is therefore to dry the structure to a moisture content below 20%. As a secondary remedial measure, identification and removal of infected timber is important. Application of fungicidal fluid can prevent the spread of dry rot. When dry rot is detected, it is preferable to replace the affected timber and treat the unaffected timber near the region affected. Preservative treated timber should be used for replacement.

36. Building Research Establishment (1986). **Zinc Coated Steel.** BRE Digest 305, January.

    This digest presents some of the corrosion characteristics of zinc and steel. Zinc will form a stable protective film in environments with a pH between 6 to 12.5, with a low chloride and low oxygen content. Zinc provides protection to steel in two distinct ways. If the zinc coating is continuous over the surface it provides a barrier between the steel and the corrosive environment. The corrosion rate of zinc, once its protective oxide layer has formed, is relatively low compared to that of steel. If the zinc coating is damaged and the steel substrate is exposed, zinc will provide galvanic protection by acting as a sacrificial anode. Zinc coatings can be applied to steel either by hot dip galvanizing, electrodeposition, metal spraying, or sherardising. Curves are presented which gives typical life of zinc as a function of coating thickness in various environments. Finally, corrosion of zinc in contact with various building materials is discussed.

37. Building Research Station (1966). **Durability and Application of Plastics.** Building Research Station Digest 69, April.

    Durability of plastics used in various applications in the building industry is reviewed. Sunlight, warmth and moisture are the major influences in exposure although oxygen and atmospheric pollutants play a role.

Ultraviolet radiation initiates many of the chemical reactions by which plastics are oxidized and degraded. Temperature plays an important role in determining the reaction rate leading to breakdown. Moisture may physically weaken the bond between a resin and its filler or reinforcement, it may cause dimensional changes and may also lead to changes in colour. When plastics are buried in soil, attack by rats or termites may lead to failure. Typically, degradation of plastics is much faster in rural areas where the plastics are not covered by a protective layer of dirt. The most common forms of breakdown are fading, darkening, yellowing, and chalking or erosion. Loss of plasticizers or breakdown of polymer chains may cause embrittlement of plastics. Various types of plastics commonly used in the building industry are presented and their durability and applications are discussed briefly.

38. Callaghan, B.G. (1982). **Atmospheric Corrosion Testing in Southern Africa.** in *Atmospheric Corrosion*, W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 893-912.

Long-term atmospheric corrosion exposure programs have been established throughout Southern Africa by the Council for Scientific and Industrial Research (CSIR). The paper presents the results of various national research projects aimed at evaluating the performance of metals and metal coatings. A 20-year exposure program showed that the corrosion rate for mild steel, Cor-Ten, copper, aluminum, and stainless steel decreased with time. The corrosion rate for zinc increased with time in all areas of the country. Corrosion rates reported were based on mass loss and, consequently, does not reflect pitting. Corrosion rates from 0.23 mil/yr (in dry polluted areas) up to 10.1 mil/yr (marine environment) have been reported. Except for one exposure site close to the sea, Cor-Ten showed lower corrosion rate than plain carbon steel. The presence of industrial pollution was found to increase significantly the rate of corrosion even in the dry inland areas. The excellent protection against corrosion afforded to steel by thermally sprayed aluminum coatings lead the authors to recommend further consideration for this system in areas where corrosion is severe.

39. Calvo, L. and M. Meyers (1991). **Overlay Materials for Bridge Decks.** *Concrete International*, Vol. 13, No. 7, pp. 46-47.

The authors advocate the use of polymer overlays to provide a protective barrier to bridge decks. The conventional asphaltic overlays do not provide the appropriate wear or skid resistance and add considerable weight to the deck. The polymeric materials are usually thinner and therefore lighter and do not require extended bridge closure during installation of the system.

40. Canovas, M. F., N. H. Selva and G. M. Kawiche (1992). **New Economical Solutions for Improvement of Durability of Portland Cement Mortars Reinforced with Sisal Fibres.** *Materials and Structures*, Vol. 25, pp. 417-422.

Vegetable fibres are sometimes used as a reinforcement of Portland cement mortar. Their decomposition with time due to their inherent weakness in this environment represents a significant problem. The research program was carried out with the aim of solving the problem of vegetable fibre mineralization. The work showed that the use of natural products derived from timber can reduce the mineralization of vegetable fibres in cement mortars. The products used showed a good efficacy in alkaline reduction, mortar pore sealing, and reduction of water absorption in the mortars and fibres.

41. Carter, P. D. (1991). **Sealing to Improve Durability of Bridge Infrastructure Concrete.** *Concrete International*, Vol. 13, No. 7, pp. 33-36.

The author relates his own experience with the use of concrete sealers on bridges in Alberta. Concrete sealers are believed to be effective at reducing the rate of deterioration of concrete curbs exposed to severe corrosive environments. "The need for curb repairs on the Alberta bridge system has been significantly reduced since the early 1980's when routine sealing with acrylic sealers replaced the previous sealing done with linseed oil in mineral spirits". The lack of standardized techniques to assess the various sealers available on the market is believed to cause much of the problems encountered when selecting a sealer for specific applications.

42. Carter, J.P., P. J. Linstrom, D. R. Flinn, and S. D. Cramer (1987). **The Effects of Sheltering and Orientation on the Atmospheric Corrosion of Structural Metals.** *Materials Performance*, Vol. 26, No. 7, July, pp. 25-32.

The authors describe the results of a field exposure program of four metals: carbon steel, Cor-Ten A weathering steel, copper, and zinc. Samples were exposed to the open atmosphere with either one side (skyward or groundward) masked, or both sides exposed and some specimens were sheltered under a transparent plastic cover. It was found that the average corrosion loss of specimens masked (average of skyward and groundward exposure) coincided to the corrosion loss of specimens exposed on both faces, except for zinc which showed a lower corrosion loss when exposed on both faces than the average of skyward and groundward exposure. This is believed to be the result of galvanic action between the two exposed faces. The corrosion loss on the skyward face was found to be greater for zinc and copper. The opposite was observed for both steels. The sulfur content in the corrosion layer was found to be greater for the boldly exposed steel than on the sheltered corrosion film. The reverse was found to be correct for zinc and copper.

This was explained by the action of rain washing the corrosion products on zinc and copper. The steel corrosion film was not as much dissolved by rain water. For the same reason, the groundward corrosion film for steel was found to contain more sulfur. The limiting sulfur concentration in the corrosion films formed on sheltered and boldly exposed zinc panels suggested that in some gross way, the zinc corrosion film can be saturated with sulfur. This was not observed for the other metals.

43. Chen, S., H. Huang, C. Liu, and Y. Pan (1992). **Technique for Detecting Sensitization in Austenitic Stainless Steel.** *Corrosion*, Vol. 48, No. 7, pp. 594-598.

The use of potentiostatic pulse technique has been shown be effective in detecting sensitization of austenitic stainless steel. Compared with the conventional electrochemical potentiokinetic reactivation test, the latter technique is found to be faster and is almost nondestructive

44. Cohen, J.M. and P.J.M. Monteiro (1991). **Durability and Integrity of Marble Cladding: A State-of-the-Art Review.** ASCE *Journal of Performance of Constructed Facilities*, Vol. 5, No. 2, May, pp. 113-124.

Marble is a nontraditional cladding material for high-rise buildings. The improvement in cutting processes in the last few years have allowed panel thicknesses to decrease markedly. As a result, problems have developed with marble cladding on buildings which are no more than 20 years old. Expensive replacement work of marble cladding on the Lincoln First Tower in Rochester and on the Amoco Building in Chicago is the result of the most common problem with thin marble panels, namely permanent bowing of the material. The authors outline the research that has been done on the use of stone cladding on buildings over the past century. It seems that the cause of the problem with marble panels is not well understood but it is most likely related to the crystal structure of the marble. The most important agents for the deterioration of marble are pollutants such as carbon dioxide, nitric acid, and especially sulfur dioxide. The dolomitic marbles are more resistant to corrosive agents than calcite marbles. The authors indicate that there is a significant lack of proper guidelines for selecting and testing marble's durability and stability. The present ASTM standard tests do not provide the basis for a comprehensive test program.

45. Cramer, S., J.P. Carter, P.J. Linstrom, and D.R. Flinn (1988). **Environmental Effects in the Atmospheric Corrosion of Zinc.** *Degradation of Metals in the Atmosphere,* ASTM STP 965, S.W. Dean and T.S. Lee, Eds., American Society for Testing and Materials, Philadelphia, pp. 229-247.

As part of the NAPAP (National Acid Precipitation Assessment Program) work, field exposure corrosion tests are conducted. The authors present some of the results obtained from zinc corrosion tests. The paper discusses seasonal variations in air quality and rain chemistry at four exposure sites in the U.S. The effect of environmental conditions on the nature of the corrosion film chemistry is investigated. The test data, obtained over a three-year period, showed evidence that the corrosion film consists of an outer layer that is relatively unprotective, and an inner layer sensitive to sulfur dioxide (SO_2) concentrations that controls the corrosion process in long-term exposures. Measurements of SO_2 levels in the air indicated that the maximum level usually occurs during winter and the minimum occurs during summer. This is in good agreement with patterns related to regional energy demands. Monitoring of the hydrogen ion loading of the precipitation showed that the maximum value usually occurs during the summer while the minimum amount occurs during winter. No explanation for this 6-month offset is given. As a result of an analysis of the test data, a damage function was proposed which relates the precipitation pH and quantity to the zinc runoff loss.

46. Davies, H. (1990). **Studies of the Performance of Fusion Bonded Epoxy Coated Reinforcement During the Construction Process.** *Protection of Concrete*, R.K. Dhir and J.W. Green, editors, Proceedings of the International Conference, held at the University of Dundee, Scotland, U.K., 11-13 Sept., pp. 269-280.

The authors presents an historical review of the use of epoxy coated reinforcement in the U.S., Canada, and the U.K. He reports on the results of site trials of epoxy coated reinforcement designed to assess the damage sustained by the coating during 1) transport and site storage, 2) preparation of reinforcement cage, 3) placement and compaction of concrete. The test specimens were small walls. The steel was examined before placement of the concrete and it was found that 40 percent of the bends had holidays. After the concrete was placed and vibrated, the concrete was removed and the reinforcement was washed. An average of 7.8 defects (where the steel was exposed) per meter of rebar were detected. Placement and vibration of the concrete was found to inflict significant damage to the coating. The use of a vibrator in the forms was found to be the main cause of damage during placement of the concrete. In general, although the damage to the coating before placement of the concrete was within acceptable limits set by British codes, those damages were found to exceed the limits after placement of the concrete. The author advises caution in the use of epoxy coated rebars since the implications of his findings on the durability of reinforced concrete are not yet known.

47. Dhir, R. K., P. C. Hewlett and Y. N. Chan (1990). **Assessment of Concrete Durability by Intrinsic Permeability.** *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 503-513.

The intrinsic permeability of concrete was measured using air test and water test. Although the air tests did not give the same results as the water permeability tests, a correlation was found to exist between the two tests. It was shown that the compressive strength of concrete alone should not be used as a means of assessing its permeability potential since no direct relationship exists between strength and permeability. The paper does not cover any aspect of concrete durability other than the fact that the authors mention in their abstract that the link between measured permeability and durability is currently being studied.

48. Edgell, G.J. (1987). **The Resistance to Corrosion of Steel in Reinforced and Prestressed Masonry.** In *Durability of Construction Materials.* Proceedings of the First International Conference held by RILEM, Versailles, France, Sept. 7-11, pp. 1021-1024.

The paper describes the provisions for the protection of steel in masonry given in BS 5628: Part 2. The code suggests the type of steel (plain carbon steel, galvanized steel, austenitic stainless steel) to be used if durability is to be obtained in various environments. The sites are classified into categories E1, E2 and E3 using the exposure to wind driven rain. The basis of the classification is the amount of wind driven rain falling on a vertical surface during the worst likely spell of bad weather in a three year period. The fourth exposure condition is for severe exposure whereby the masonry is exposed to salt or moorland water, corrosive fumes, abrasion or de-icing salts. Under those severe exposure conditions, E4, the code specifies the use of austenitic stainless steel or carbon steel coated with at least 1 mm of stainless steel. Special requirements are also placed when the porosity of the materials used (brick, block or mortar) exceeds a certain limit. The code also considers the situations where protection is given by concrete cover rather than by the steel resistance to the environment.

49. Fassina, Vasco (1988). **Environmental Pollution in Relation to Stone Decay.** *Durability of Building Materials*, Vol. 5, Nos. 3&4, pp. 317-358.

The paper presents the various sources of atmospheric pollutants such as sulfur compounds, nitrogen oxides, ozone, hydrogen chloride, carbon dioxide. The corrosion reaction associated to each compound is also presented along with discussion of their implication on stone decay.

50. Feliu, S. and M. Morcillo (1982). **Atmospheric Corrosion Testing in Spain.** in *Atmospheric Corrosion.* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 913-921.

Field and laboratory testing are extensively used to study the problem of atmospheric corrosion in Spain. The authors present a description of the field testing program which includes a network of test sites covering various types of environment such as urban, industrial, marine, and rural. One of the objectives of the field tests is to correlate corrosion data with meteorological data. Relative humidity, temperature, precipitation and the number of days with rain are recorded. In addition, the SO_2 and chloride levels are being monitored at various sites. The time-of-wetness is generally taken as the time during which the relative humidity is greater than 85 percent. Assuming that the time-of-wetness was almost constant at various test sites with varying level of sulfur dioxide, it was shown that the corrosion losses for steel exposed to an atmosphere containing 0.5 mg SO_2/dm^2/day was about 30% lower than in an atmosphere having 1.75 mg SO_2/dm^2/day. The effect of SO_2 on zinc was found to be more marked than on steel (the rate of corrosion of zinc under the same change of SO_2 was halved).A study of long-term atmospheric corrosion showed that the bilogarithmic equation fitted well the observed rates of corrosion for steel, zinc, copper, and aluminum after three years of exposure in open and sheltered environments. It was observed that, whereas the rate of corrosion decreases with time in the open atmosphere, it remains fairly constant in a sheltered environment. This behaviour can be expected if the rust formed on the metal surface is not protective, but rather a source of moisture capillary condensation and of accumulation of pollutants.

51. Flinn, D.R., S.D. Cramer, J.P. Carter, and J.W. Spence (1985). **Field Exposure Study for Determining the Effects of Acid Deposition on the Corrosion and Deterioration of Materials - Description of Program and Preliminary Results.** *Durability of Building Materials*, Vol. 3, No. 2, pp. 147-175.

As part of the research activities of Task Group G - Effects on Materials, within the National Acid Precipitation Assessment Program (NAPAP), the Bureau of Mines (BOM), U.S. Department of the Interior has initiated a field-exposure program to study the effects of acid deposition on the corrosion and deterioration of metals commonly used in outdoor structures. Structural metals are exposed at five different sites. At each site the air quality (SO_2, NO, NO_x, NO_2, O_3) , meteorology (wind speed and direction, temperature, relative humidity, precipitation, solar radiation, and surface wetness time and events) and rain chemistry (pH, cations and anions) are continuously measured. The test program and the preliminary results

after two years of exposure of the test samples are presented. The metals investigated are: 1010 Carbon steel; Cor-Ten A steel; 110 Copper; 3003-H14 Aluminum; 191 Zinc; Galvanized steel; and Galvalume. Concentration of sulfur in the corrosion films of all the metals is higher on the groundward side than on the skyward side for one-month exposure. Dry deposition of neutralizing particles on the skyward side, coupled with washing by rain, probably accounts for this difference.

52. Ford, P. and D. J. H. Corderoy (1975). **The Corrosion Characteristics of Galvanized Reinforcing Bar.** Proceedings of the Sixth International Congress on Metallic Corrosion, Sydney, Australia, December, pp. 1508-1516.

Experimental results showed that the galvanized bar improved the corrosion resistance of reinforcement embedded in concrete at depth of cover from 10 mm and 20 mm when subjected to impressed currents. The corrosion resistance of galvanized bars in a natural marine environment was greater than that of the black bar. The black bar was heavily coated with rust whereas the galvanized bar was protected by the zinc coating. The lowest overall corrosion rate for the galvanized coating is in the pH range of 7 to 12, and as such the coating is able to withstand a lowering of the pH due to carbonation of the concrete to a greater degree that the steel reinforcement. Above a pH of approximately 12.5, the zinc reacts rapidly with the alkaline environment to form soluble zincates. This occurs when the zinc coating is placed in wet cement. When the galvanized coating has been passivated the steel-concrete bond is superior for the hot dip galvanized bar than for the black bar.

53. Fukushima, T., N. Sato, Y. Misamatsu, T. Matsushima, and Y. Aoyama (1982). **Atmospheric Corrosion Testing in Japan.** in *Atmospheric Corrosion*, W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 841-872.

The cost of corrosion protection in Japan has been evaluated at 1.9% of the gross national product ($12 billion) in 1974. Over 60% of that cost can be attributed to atmospheric corrosion alone. Various exposure sites have been established throughout Japan under the supervision of the Japan Weathering Test Center. Corrosion testing of carbon and weathering steels (conducted by the Research Group on the Corrosion Protection of Steel Frame Structures) showed that the time-corrosion curves can be described well by the bilogarithmic law. Multiple regression analysis of the test data indicated that the temperature, the relative humidity, the chloride concentration, the sulfur dioxide concentration and the amount of rainfall had a significant influence on the rate of corrosion. A regression equation has been presented. Exposure test results are presented for aluminum and its alloys, stainless steels, and coated steels. Studies on the nature and properties of atmospheric corrosion products of various metals are presented. Finally, a description of accelerated corrosion tests developed by the Japan Society of Steel Construction is briefly discussed.

54. Gatto, F. and A. Perrone (1982). **Atmospheric Corrosion Testing of Aluminum in Italy.** in *Atmospheric Corrosion*, W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 827-839.

The authors present the results of an investigation of the atmospheric corrosion of aluminum conducted by the Istituto Sperimentale dei Metalli Leggeri (ISML) since the early 1950s. Marine, industrial and urban test stations were established. The influence of anodizing the surface was investigated in the three atmospheres. It was found that in order to offer good protection, the thickness of anodized aluminum had to be greater as the impurity level in the alloy increases and the structure of metallic compounds becomes coarser. It was found that a 24-µm film obtained through a good sulfuric acid process did not show significant corrosion after nine years of exposure in an urban-industrial area.

55. Graedel, T.E. and R. McGill (1986). **Degradation of Materials in the Atmosphere.** *Environmental Science Technology*, Vol. 20, No. 11, pp. 1093-1100.

The paper presents a general summary of the problem of corrosion in the atmosphere. The authors discuss topics such as the assessment of the degradation potential of the atmosphere (the atmosphere contains various corrosive elements which are occurring either naturally (oxygen and carbon dioxide) or the result of pollution (sulfur)), degradation by rain and snow, degradation by airborne particles, degradation by dew and fog, and indoor degradation. The authors also discuss the synergistic effects of the various corrodents.

56. Grube, H. (1987). **Measuring Gas Permeability of Concrete for Assessing Factors of Durability.** in *Durability of Construction Materials*, Proceedings of the First International Conference held by RILEM, Versailles, France, Sept. 7-11, pp. 1206-1213.

The oxygen permeability has been found to be a suitable indicator to measure the open porosity and its changes in relation to concrete composition and curing. Concrete which is commonly regarded to be suitable for outdoor exposure ($w/c \leq 0.60$ and medium curing) showed coefficients of permeability of less than 10^{-16} m^2. It was found that concrete with $w/c = 0.8$ and cured extremely well can reach the same permeability as a badly cured concrete with $w/c = 0.6$. The tests described by the author showed that in the range of low permeability there seems to be a linear correlation between permeability and carbonation depth. It was found that the permeability measurements were strongly influenced by the thickness of the specimens used for the measurement. This may be explained by the increase in probability for local defects such as pores being able to connect the testing surfaces. Specimens with a 50 mm thickness were mostly used in the investigation. In general, the compressive strength of standard cubes seemed to be unsuitable to predict permeability or carbonation in progress.

57. Guttman, H. (1968). **Effects of Atmospheric Factors on the Corrosion of Rolled Zinc.** in *Metal Corrosion in the Atmosphere,* ASTM STP 435, American Society for Testing and Materials, pp. 223-239.

A long term exposure program has been carried out at Birchbank, B.C., where rolled zinc corrosion data and certain atmospheric factor data were obtained. Zinc is sensitive to variations in climatic and atmospheric pollution conditions, and, as a result, panels exposed on different dates for a specific period of time can corrode at different rates. An empirical equation has been developed for Birchbank which relates corrosion of zinc to the time of wetness of exposed panels and the average atmospheric sulfur dioxide content during the time panels are wet. The equation accounts for most of the observed variations in corrosion losses and is valid for exposure periods of up to 256 weeks duration. The paper also presents information concerning the relative corrosion rates of the skyward and groundward surfaces of zinc panels, the relationship between time of panel wetness and relative humidity, and the relationship between atmospheric sulfur dioxide as measured by a Thomas autometer and by the lead peroxide method.

58. Guttman, H. and P.J. Sereda (1968). **Measurement of Atmospheric Factors Affecting the Corrosion of Metals.** *Metal Corrosion in the Atmosphere,* ASTM STP 435, American Society for Testing and Materials, pp. 326-359.

Atmospheric factors such as time-of-wetness, panel temperature, atmospheric sulfur dioxide and atmospheric chloride content were measured at four inland and three coastal North American test sites while corrosion data for steel, copper, and zinc were being developed. Statistical analysis showed conclusively that the measured atmospheric factors completely controlled the rates of corrosion at all sites for at least the first month. For longer term exposures the atmospheric factors control the corrosion of zinc under most conditions investigated and of steel and copper at the marine sites. With steel and copper at the inland sites it was assumed that control of the corrosion process is gradually transferred from the atmospheric factors to factors related to the changing surface condition resulting from accumulation of corrosion products and foreign agents. This appeared to be true in all cases except steel at Ottawa and copper at South Bend. The results of this research program indicated an area of future work concerned with the character of corrosion products which form on the surface of a corroding specimen and which modify the primary control of the atmospheric factors on the rate of corrosion of metals. (References are given for techniques of SO_2 and chloride measurement techniques).

59. Haagenrud, S.E. (1985). **Mathematical Modelling of Atmospheric Corrosion and Environmental Factors.** in *Problems in Service Life Prediction of Building and Construction Materials.* L. W. Masters, Ed., Martinus Nijhoff Publishers, pp. 229-252.

The corrosivity of the atmosphere is described by so-called dose-response relationships obtained by field tests at various sites in Scandinavia. The author describes the lab and field studies carried out by the Norwegian Institute for Air Research (NILU) to establish dose-response relationships for steel and zinc. It was found that long term corrosion rates cannot be estimated directly from short term measurements of corrosion rate. The rate of corrosion can increase or decrease with time depending on the characteristics of the atmosphere. In general, the rate of corrosion was observed to decrease with time, but the rate of decrease varies significantly from region to region. The sulfur dioxide and chloride concentration were found to have a significant impact on the rate of corrosion. The short term (one year) dose-response functions were used to classify the atmospheres according to corrosivity. An exponential rate model is proposed for the prediction of long term corrosion rate.

60. Hakkarainen, T. and S. Yläsaari (1982). **Atmospheric Corrosion Testing in Finland.** in *Atmospheric Corrosion,* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 787-795.

The aggressivity of the atmosphere in Finland is believed to be generally low. As a consequence, not much attention has been given to the problem of atmospheric corrosion in the past. However, since the direct application of test results from other countries may be misleading when applied in Finland, more research has been directed toward that problem since 1968 when the first test site was brought into use. The main part of the testing is directed by the Technical Research Center of Finland. Steel producers and paint manufacturers also have their own testing facilities. A brief description of the five test sites (all located in southern Finland) owned by the Technical Research Center is presented. The test results on mild steel have shown that the rate of corrosion can be described by the bilogarithmic law. The results of test on weathering steels, galvanized steel, aluminum and copper alloys, and stainless steels are discussed. The test results so far have shown that the corrosion rates are indeed very low.

61. Harrison , W.H. and M.E. Gaze (1989). **Laboratory-Scale Tests on Building Mortars for Durability and Related Properties.** *Masonry International*, Journal of the British Masonry Society, Vol. 3, No. 1, pp. 35-41.

Small specimens of mortar made by normal brick-laying techniques were subjected to wet/dry, freeze/thaw cycles to simulate severe exposure. A total of 84 mixes, made with two types of cement, seven different sands, two types of mortar, and three levels of cement content, were investigated. Specimens of mortar beds laid between pairs of dry porous bricks had higher strength, lower carbonation rates and better durability than specimens laid between saturated or low absorption bricks which exerted no suction. Durability was assessed by the amount of degradation after exposure to 25 cycles of frost, sulfate or the combination of sulfate and frost. Resistance to frost was increased by the presence of entrained air. Only the air-entrained mortars made with sulfate-resisting Portland cement and a cement to sand ratio of at least 1:6 were resistant to the combination of frost and sulfate. It is estimated that for mortars with cement contents from 120-300 kg/m^3, the minimum times for carbonation of 100 mm joints in internal walls would vary from 1.5 to 4.5 years depending also on the mortar type.

62. Haver, C.A. (1989). **Corrosion of Steel Embedded in Masonry Walls.** *Material Performance*, Vol. 28, No. 12, Dec. pp. 44-46.

The paper is a student poster based on a senior project for a bachelor's degree. The paper presents the results of an investigation of the corrosion of reinforcing steel embedded in a seawall. A half-cell potential contour map is presented and ASTM guidelines are used to interpret the contour map. The study showed that half-cell potential surveys conducted in accordance to ASTM C 876 cannot predict the presence or absence of corrosion in masonry walls. Carbonated masonry mortar was found to be protective of embedded steel, and the embedded steel did not corrode, even in the presence of environmental chlorides.

63. Haver, C.A., D.L. Keeling, S. Somayali, D. Jones, and R.H. Heidersbach (1990). **Corrosion of Reinforcing Steel and Wall Ties in Masonry Systems.** (refer to Case Studies)

64. Haynie, F.H. (1982). **Evaluation of the Effects of Microclimate Differences on Corrosion.** *Atmospheric Corrosion of Metals*, ASTM STP 767, S.W. Dean, Jr., and E.C. Rhea, Eds., American Society for Testing and Materials, pp. 286-308.

The author presents the results of a statistical analysis of weather data and data from Manfeld's Atmospheric Corrosion Monitors (ACM) (these monitors are galvanic cells of copper/zinc and copper/steel). The ACM's were used to indicate the magnitude of corrosivity as well as time-of-wetness. Since covariance exists between some of the variables measured the large set of data collected was partitioned into small subsets. It was found that corrosion rates are strongly dependent on relative humidity (the time-of-wetness was related to the relative humidity through regression analysis of the field data), the flux to the surface of total oxides of nitrogen, and the flux to the surface of total sulfur. The relative humidity was found to be the most significant factor and was also found to be the factor the most in error since R.H. was not always measured at the site where the ACM's were located. For both the steel and the zinc ACM's, temperature and relative humidity affected corrosion rate in increasing order of significance.

65. Haynie, F.H. (1978). **Theoretical Air Pollution and Climate Effects on Materials Confirmed by Zinc Corrosion Data.** First International Conference on Durability of Building Materials and Components, ASTM STP 691, pp. 157-175.

The author attempts to evaluate the applicability of theoretical damage functions for zinc and galvanized steel. The author states that surfaces contaminated with sea salt are expected to be wet when the relative humidity exceeds 75 percent. Deposition rate of SO_2 is calculated from the horizontal wind velocity. Using calculated deposition velocity and knowing the stoichiometry of the corrosion reaction, a damage function can be obtained. Unfortunately, the author does not present the damage function that he did obtain. Comparison of predicted value with theoretical predictions is discussed but the results are not clear. Test results of corrosion rate of zinc obtained by other researchers are presented but, unfortunately, TOW reported by the author is obtained from the average relative humidity over a long period of time and an expression derived by the author and calibrated by measurements made at sites other than the test sites where corrosion rates were measured. TOW for another set of data reported by the author is not reported. Although the paper presents some interesting concepts it is hard to follow the logic. The comparison of apparently theoretical predictions with experimental results is very obscure.

66. Haynie, F.H. and J.B. Upham (1974). **Correlation Between Corrosion Behavior of Steel and Atmospheric Pollution Data.** *Corrosion in Natural Environments*, ASTM STP 558, American Society for Testing and Materials, pp. 33-51.

Atmospheric corrosion tests on enameling steel at 57 sites showed that the average relative humidity and level of sulfate in suspended particulate or average level of sulfur dioxide had a significant effect on the depth of corrosion on the tested samples. According to statistical analysis, differences in average temperature, average total suspended particulate, and average nitrate in suspended particulate caused insignificant changes in the steel corrosion rate. Sulfur dioxide was a significant variable only when sulfate in suspended particulate was not included in the regression analysis.

67. Hilsdorf, H.K. (1989). **Durability of Concrete - a Measurable Quantity?.** *Durability of Structures*, IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/1, pp. 111-124.

The author investigated if the air permeability of concrete only is suitable to characterize concrete durability in a general way. The characteristic air permeability coefficient K_{AC}, defined by the author, correlates well with the progress of carbonation under laboratory conditions. Effects of water/cement ratio and curing are reflected by K_{AC}. However, if cements containing larger amounts of components other than portland cement clinker is used, the relation between depth of carbonation and K_{AC} is no longer unique. The author concludes that concrete air permeability is not the unique parameter to describe concrete durability, and it is unlikely that such a parameter exists. The author proposed an expression to calculate the depth of carbonation as a function of time and concrete permeability.

68. Ho, D.W.S, F.D. Beresford, and R.K. Lewis (1984). **Durability of Above-Ground Structures as Affected by Concrete Constituents.** Third International Conference on the Durability of Building Materials and Components, (Vol. 3), Espoo, Finland, August 12-15, pp. 163-175.

The authors present test results from other researchers to demonstrate that concrete of comparable strength and slump, but of different constituents, do not necessarily carbonate at the same rate and the ease of water movement and the quality of the concrete (as indicated by water penetration) can vary over a wide range. The curing time was found to affect significantly the permeability of concrete.

69. Hoff, G.C. (1991). **Durability of Offshore and Marine Concrete Structures.** *Durability of Concrete*, Second International Conference, Montreal, Canada, ACI SP-126, Vol. 1, V.M. Malhotra, Editor, pp. 33-64.

The paper reviews the deterioration mechanisms of concrete (wetting and drying, freezing and thawing, abrasion by ice, chemical attack or mineral depletion by water, salt accumulation, attack by marine organisms). It also reviews the recent trends in strength development for concretes made with modern materials. The author concludes that the key factor to improve the durability of concrete in sea water is to make the paste fraction of the concrete less permeable by: 1) lowering the w/c ratio as low as practical; 2) adding finely divided siliceous material to all concrete such as natural pozzolans; 3) requiring sufficient amounts of cement and cementitious materials in the concrete.

70. Horton, J.B., A.R. Borzillo, G.J. Harvey, and J. Reynolds (1975). **Corrosion Characteristics of Zinc, Aluminum and Aluminum-Zinc Alloy Coatings on Steel.** Proceedings of the Sixth International Congress on Metallic Corrosion, Sydney, Australia, December, pp. 794-801.

The corrosion behaviour of three hot dip metallic coatings was investigated. The systems investigated were, hot dipped galvanized steel, aluminized steel, and galvalume sheet. The latter is an aluminum-zinc alloy developed by the Bethlehem Steel Corporation and comprising 55% aluminum, 1.5% silicon, with the balance zinc. The mechanism of corrosion of hot dip galvalume steel was investigated by examination of the coating structures before and after exposure at exposure sites in the U.S. and Australia. The results show that, initially, the zinc-rich phase corrodes preferentially, at a slower rate than galvanized coatings, and as this phase becomes depleted, or is replaced with corrosion product, the corrosion rate decreases further and becomes more characteristic of the aluminum-rich phase. Galvanic protection is provided at sheared edges, either by the zinc-rich phase corroding preferentially, or by both phases, depending on the chloride content of the environment. Comparative corrosion rate measurements showed that galvalume coatings are generally about 2 to 4 times as corrosion resistant as galvanized coatings of equal thickness.

71. Idorn, G.M. (1991). **Concrete Durability & Resource Economy.** *Concrete International*, Vol. 13, No. 7, pp. 18-23.

The author discusses the changes that took place over the years in the construction industry and technology and how those changes modified the durability of concrete. The technological developments in the concrete industry have brought significant improvements in the conventional concrete. The use of conventional

portland cement with aggregates is now a thing of the past. The changes made over the years have affected the way in which the concrete is produced, placed, and cured. Use of chemical additives in concrete has rendered the use of vibration and early curing less critical. Unfortunately, the control of the quality is not up to date with the technological changes which took place in the product. Better tests have to be devised to assess concretes for effects such as alkali-aggregate reactivity, etc... Pointing at the research performed in the field of forensic engineering, the author states that the technology to replace the conventional standard sample testing seems within reach.

72. Johansson, L.-G., O. Lindqvist, and R.E. Mangio (1988). **Corrosion of Calcareous Stones in Humid Air Containing SO_2 and NO_2.** *Durability of Building Materials*, Vol. 5, pp. 439-449.

Three type of stone samples (limestone, marble, and travertine) were exposed to synthetic gas mixtures containing NO_2 and SO_2. Those pollutants are found in increasing amounts in the atmosphere as a result of combustion of fossil fuels. The results of the exposure tests showed that SO_2 generally has a greater influence on the corrosion of polished stones than NO_2. However, the addition of NO_2 to SO_2 containing atmosphere was found to increase the corrosion substantially. The tests were conducted at a high relative humidity of 90 percent. The synergistic effect was not observed at a relative humidity of 50 percent. The composition of the corrosion products was investigated and the possible reaction scheme for the interaction of SO_2 and NO_2 with the stone surface was proposed.

73. Justo, M.J. and M.G.S. Ferreira (1993). **The Corrosion of Zinc in Simulated SO_2 - Containing Indoor Atmospheres.** *Corrosion Science*, Vol. 34, No. 4, pp. 533-545.

Electrochemical tests were carried out on zinc/zinc cells covered with a thin layer of zinc sulfate to simulate atmospheres containing 20, 50 and 75 $\mu g/m^3$ of SO_2 and a relative humidity of 85 %. The testing procedure using $ZnSO_4$ assumes that the first step in the corrosion process by SO_2 is the oxidation of SO_2 to sulfate. The tests try to simulate indoor environment since the effect of rain is not considered. Current density and impedence were measured after the specimens were exposed to the test solution and placed in a dry or 85% RH atmosphere for drying. The results showed that the corrosion rates are higher for the lower concentration of equivalent SO_2. The drying time for the higher concentrations was higher than for the low concentration, which is contrary to the case for iron. The amount of sulfate in the corrosion products increases with the equivalent concentration of SO_2. However, in outdoors exposure, the washing off of the corrosion products by rain stimulates the dissolution of the sulfate formed, with the corrosion products layer being continually re-established by hydroxide/oxide formation.

74. Knotkova, D., K. Barton, and M. Cerny (1982). **Atmospheric Corrosion Testing in Czechoslovakia.** in *Atmospheric Corrosion*, W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 991-1014.

A brief discussion on the use of various types of corrosion tests from long-term field tests to laboratory accelerated corrosion tests is presented. General principles for establishing and utilizing test stations are also discussed. A brief presentation of station networks and sites description are presented. The central Czechoslovak station network is supported by the systematic research on atmospheric corrosion which has been carried out by the State Research Institute of Material Protection since the early 1950's. Meteorological and aerochemical measurements performed at the test stations enable the calculation of the time-of-wetness, taken as the time during which the relative humidity is greater than 80% while the temperature is above freezing. Regression analysis of field exposure test results has shown that the time-of-wetness and SO_2 levels better characterize the aggressivity of open atmospheres for steel, zinc, and copper, and, in a less obvious manner, of an environment protected against the effects of precipitation.

75. Kucera, V. (1985). **Influence of Acid Deposition on Atmospheric Corrosion of Metals: A Review.** ACS Symposium Series 318, Baboian, Editor, pp. 104-118.

The author presents a brief review of the influence of acidifying air pollutants on the atmospheric corrosion of metals based mainly on more recent results from Europe and especially from Scandinavia. Research has shown the dominating effect of SO_2 on the corrosion rate of carbon steel and zinc. Dose-response functions, in terms of the SO_2 level only, have been derived based on corrosion rate measurements. The inclusion of time-of-wetness in the linear models does not always improve the correlation. The effect of NO_x alone on the corrosion of steel was found to be negligible. However, NO_x was found to increase significantly the rate of corrosion in the presence of SO_2 at a RH of 50% but the synergistic effect was not observed at 90% RH.

76. Kucera, V., S. Haagenrud, Lyder Atteraas, and J. Gullman (1988). **Corrosion of Steel and Zinc in Scandinavia with Respect to the Classification of the Corrosivity of Atmospheres.** *Degradation of Metals in the Atmosphere,* ASTM STP 965, S.W. Dean and T.S. Lee, Eds., American Society for Testing and Materials, Philadelphia, pp. 264-281.

Exposure test results on steel and zinc at 32 sites in Scandinavia are presented. The tests were performed on standard specimens. Measurements were taken of the air SO_2 concentration, precipitation SO_4 and chloride concentration, precipitation pH, temperature, and relative humidity. The time-of-wetness was defined as the time during which the relative humidity was greater than 80% and the temperature above freezing. Statistical analysis was performed on the test results collected over a period of eight years for steel and over four years for zinc. A bilogarithmic relation between rate of corrosion and time was used for steel while a linear relation was used for zinc. The constants in the two models were found from a regression analysis to be functions of SO_2 and Cl^- concentration. The difference in corrosion rates observed between sites was found to be a result of the pollution level rather than climatic conditions. It was found that the corrosion rate was greater during the first and second year of testing at sites where precipitations were high. A system of classification of corrosivity was proposed based on levels of SO_2 and chlorides in the atmosphere.

77. Kucera, V. and E. Mattson (1982). **Atmospheric Corrosion of Bimetallic Structures.** in *Atmospheric Corrosion*, W. H. Ailor, Ed., John Wiley and Sons, New York, pp. 561-574.

The following parameters of importance are discussed: the electrode potential difference, the anodic and cathodic polarization and the existence of passivating coatings, the distance between anodes and cathodes, the thickness of the moisture film on the surface, and the influence of atmospheric pollution. Some field test methods are described including the circular disk method, the wire-on-bolt method, combination of plates of dissimilar metals, and electrochemical test methods. Important published investigations are surveyed, and some charts, useful in materials selection, are presented.

78. Lipfert, F.W. (1987). **Effects of Acidic Deposition on the Atmospheric Deterioration of Materials.** *Materials Performance*, Vol. 26, No. 7, July, pp. 12-19.

The author discusses the sources of acidic deposition, the general mechanisms by which acidic deposition acts to reduce material service life, the derivation of damage functions to predict such losses, and the potential economic consequences. It is estimated that 2/3 of the precipitations acidity is attributed to sulfate and 1/3 with nitrate. Damage functions for zinc, copper, steel, aluminum, stone, and mortar are presented. The agents considered in the functions are: SO_2, time-of-wetness estimated from RH statistics, annual precipitation, precipitation pH, chloride ion deposition rate, and dust deposition rate. The importance of acidic deposition upon corrosion of various building materials has been demonstrated by means of charts.

79. Livingston, R.A. (1990). **Improved Prediction of Masonry Durability Through Advanced Materials Science Methods.** in *Serviceability and Durability of Construction Materials*, Proceedings of the First Materials Engineering Congress, Denver, CO., Aug-13-15, Vol. 1, pp. 482-490.

The paper emphasizes the need to know and learn more about the durability of materials. The author suggests that the application of materials science should be useful to understand better the factors which affect the durability of masonry. No guidance is given on how to use materials science for prediction of durability or even to improve the predictions.

80. Loo, Y.H. and S.K. Ting (1990). **Effects of Pulverized Fuel Ash on Corrosion of Steel in Concrete.** in *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 145-150.

The authors present the results of an experimental investigation of the effect of fly ash addition on the corrosion of steel in concrete. Small cylindrical mortar specimens with a 13 mm rebar placed at the center of the specimens were used for the experiments. The results show the beneficial effect of fly ash addition on the corrosion resistance of the rebars after 91 days. The importance of the water to cement + fly ash ratio was demonstrated. The increased corrosion resistance was associated to the reduced pore sizes resulting when fly ash is added to the concrete mix.

81. Mangat, P. S. and B. T. Molloy (1992). **Factors Influencing Chloride-Induced Corrosion of Reinforcement in Concrete.** *Materials and Structures*, Vol. 25, No. 151, August/September, pp. 404-411.

The paper presents the results of a corrosion investigation on rebar electrodes embedded in concrete prisms which were exposed to cycles of sea-water spray for up to about 600 days. The experiments showed that the water/cement ratio is the dominant factor which controls rebar corrosion and a value of 0.45 is satisfactory for designing corrosion-resistant reinforced concrete. The cement content was found to have an insignificant

influence on the corrosion resistance of rebar in concrete exposed to a marine environment. The chloride and hydroxide concentration of the concrete matrix and pore fluid were found to be of secondary importance in corrosion resistant concrete. A pore fluid Cl^-/OH^- ratio of 11 was found to be acceptable.

82. Masson, G.F. (1989). **Sulfacrete - The Preferred Choice Cement for Durable Foundation Concrete and Masonry.** *Masonry International,* Journal of the British Masonry Society, Vol. 3, No. 1, May, pp. 31-33.

The author gives a description of Blue Circle Sulfacrete, a sulfate-resisting Portland cement manufactured and used in the U.K. The low tricalcium aluminate content (less than 2.5 % compared with 7-12% in current ordinary Portland cements) confers sulfate-resisting properties. The rate of carbonation in concrete made with Blue Circle Sulfacrete and designed for durability in terms of BS8110: Part 1: 1985 and well cured, is similar to that in equivalent 28 day strength ordinary Portland cement concrete.

83. McGee, E.S. (1991). **Influence of Microclimate on the Deterioration of Historic Marble Buildings.** *APT Bulletin, The Journal of Preservation Technology,* Vol. 23, No. 4, pp. 37-42.

The author remarks that deterioration of marble in buildings is not uniform. This is not only dependent on the variations in chemical, mineralogical and physical properties of the stone but also on microclimatic effects. Deterioration of marble is said to be the result of dissolution of calcite in acid rain. Although rain is believed to be a major cause of marble deterioration, a survey of existing buildings show that the problem also exists in sheltered areas. In sheltered areas, pollutants that are not regularly washed off the stone may react with moisture and calcite to form a new mineral phase on the surface (mostly gypsum). The subsequent deterioration of the marble can depend on whether the gypsum layer can be washed off by rain. A case study of the Philadelphia Merchants' Exchange building is presented. Deterioration of marble on this building was found to be strongly dependent on the exposure to rain, sun, and wind. Although no results are presented in this paper, the author mentions that instrumentation has been placed on the building to monitor the differences in the temperature, relative humidity, and dry deposition between different points on the building.

84. Meakin, J.D., D.L. Ames, and D.A. Dolske (1991). **Degradation of Monumental Bronzes.** *APT Bulletin, The Journal of Preservation Technology,* Vol. 23, No. 4, pp. 58-63.

A study of the degradation rate of bronze used for statues was conducted. The Hiker statue, commemorating the Spanish-American War veterans, was replicated more than 52 times and have been placed at different locations across the U.S. After having established that the metallurgical composition of the replicas was essentially the same, the statues were used as test samples. Since uniform corrosion loss was expected to be too small to make any significant comparison between the statues, depth of pit measurements, made on vinyl polysiloxane replicas, were used to compare the severity of deterioration of the different statues. A comparison between different statues showed that the degree of attack is significantly different between different sites. A surface runoff study from bronze markers of composition similar to that of the statues was conducted at Gettysburg National Military Park. The results of the runoff water analysis showed that dissolution of the bronze occurs without preferential removal of zinc from copper. The data showed a strong correlation between the amount of sulfate and dissolved copper. The correlation between copper and nitrates in the runoff water was not as good but a correlation seems to exist.

85. Mikhailovsky, Y.N. (1982). **Theoretical and Engineering Principles of Atmospheric Corrosion of Metals.** in *Atmospheric Corrosion.* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 85-105.

The nature of atmospheric corrosion is discussed as a combination of corrosion and electrochemical processes on metals beneath absorbed and thin phase layers of electrolytes. The effects of oxygen absorption, water molecule absorption, sulfurous gas absorption, and aerosols of salts are considered. The author makes use of field exposure test data from COMECON, which includes test sites in USSR and eastern Europe, to derive values of constants terms to use in proposed damage functions. The factors found to be significant in the corrosion of various metals and alloys are: time-of-wetness, temperature (for steel only), sulfur dioxide concentration, chlorides, and sheltering. The effect of temperature on corrosion of steel was found to be important both on the corrosion rate in an unpolluted atmosphere and on the corrosion rate adjustment for presence of sulfur dioxide. The effect of temperature was found to be insignificant on the effect of chlorides. The damage functions proposed for sheltered and boldly exposed conditions are interesting but the terms accounting for chloride and sulfur dioxide pollution are not well defined and it is not clear how those parameters are obtained. Consequently, the paper is more useful for a qualitative assessment rather than a quantitative assessment of corrosion agents.

86. Mikhailovsky, Y.N. and P.V. Strekalov (1982). **Atmospheric Corrosion Tests in the USSR.** in *Atmospheric Corrosion.* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 923-942.

Atmospheric corrosion tests have been conducted in the former Soviet Union since the 1950's. The authors present a description of the test sites, the instrumentation used, and the type of data collected at the exposure sites. The corrosion tests are performed under exposed and sheltered conditions. Although most of the paper describes the types of atmospheric conditions at various test sites, some corrosion test observations are also presented. The rate of corrosion of steel in the open atmosphere was found to decrease with time whereas the rate of corrosion in a semiclosed atmosphere was found to be almost constant. Zinc was characterized by linear corrosion kinetics. In the sheltered environment the zinc corrosion was found to grow linearly with time at a much smaller rate (5-7 times) than in the open air. For aluminum, it was found that the corrosion rate was greater in the sheltered environment than in the open atmosphere. This was accounted for by the fact that in a sheltered environment atmospheric corrosive agents accumulate on the specimen surfaces. In the open air these agents are periodically washed away by rain.

87. Millard, S.G. and K.R. Gowers (1991). **The Influence of Surface Layers Upon the Measurement of Concrete Resistivity.** *Durability of Concrete*, Second International Conference, Montreal, Canada, Vol. II, ACI SP-126, pp. 1197-1220.

The measurement of the electrical resistivity of concrete is a non-destructive technique used to assess the severity of corrosion of the reinforcing steel. The authors present a study of the effect of the surface layer resistivity, as affected by the wetting and carbonation of the surface. A theoretical analysis using classical treatment of the Laplace equation and a Finite Element Analysis were performed to investigate the effect of carbonation or wetting of the surface layer (a single surface layer) or the combined effect of wetting and carbonation (double layer). The analytical results were compared with physical measurements to validate the analysis results. It was found that a high resistivity surface layer, as could be formed by carbonation of the surface, has relatively little effect on the measurement of the underlying concrete resistivity as long as the carbonation thickness does not exceed 0.2 times the resistivity electrode spacing. Taking resistivity measurements upon a carbonated surface that has recently been wetted does however cause major difficulties and should be avoided. As shown by lab tests and finite element analysis, the wet surface layer can cause the resistivity measurement to increase by a factor of two to ten times. Taking resistivity readings on uncarbonated concrete that has a low resistivity surface moisture layer can also give rise to significant errors in the assessment of the underlying resistivity.

88. Millard, S.G., K.R. Gowers and J.S. Gill (1991). **Reinforcement Corrosion Assessment Using Linear Polarization Techniques.** in *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design.* Proceedings ACI International Conference, Hong Kong, V.M. Malhotra, Ed., ACI SP-128, Vol. 1, pp. 373-394.

While potential mapping is commonly used to indicate regions of corrosion activity, it cannot be used to assess the rate of corrosion. The authors have demonstrated that perturbative measurements of direct corrosion rates could be used in the field to asses the rate of corrosion. Linear Polarization Resistance (LPR) instrumentation, customized for reinforced concrete problems, can clearly indicate where significant corrosion is in progress and give as much information about the rate of corrosion as A.C. impedance.

89. Moresby, J.F., F.M. Reeves, and D.J. Spedding (1982). **Atmospheric Corrosion Testing in Australasia.** in *Atmospheric Corrosion,* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 745-754.

The authors describe the atmospheric corrosion research being pursued in Australia, New Zealand, and their adjacent islands. A brief description of the climatic conditions and atmospheric impurities found in various parts of Australasia is given. Field corrosion tests have been established since 1960, and the methods used are based on the U.K. or U.S. practice in almost all respects. BISRA standard copper steel samples are used by the Commonwealth Scientific and Industrial Research Organization (CSIRO) to standardize test sites. The Joint Tropical Trials and Research Establishment (JTTRE) formed by the British and Australian governments has tested service equipment in Queenland. In 1979 investigators started an intensive corrosivity survey of 900 km^2 of the Melbourne metropolis. Coupons are suspended 3.7 m above ground and are on a 2 x 2 - km grid. The aim is to plot corrosivity map to aid the local electricity authorities, engineers, and builders to select materials of sufficient corrosion resistance.

90. Nagataki, S. and H. Ohga (1992). **Combined Effect of Carbonation and Chloride on Corrosion of Reinforcement in Fly Ash Concrete.** in *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete,* Proceedings of the Fourth International Conference, Istanbul, Turkey, May, V.M. Malhotra, Ed., ACI SP-132, Vol. 1, pp. 227-244.

Mortars with and without fly ash (fly ash was used to replace some of the cement) were cured in distilled water or NaCl solutions for varying lengths of time. The samples were then exposed to accelerated carbonation. The influence of chloride ion on the depth of carbonation was thus evaluated. Samples initially cured in distilled water were exposed to accelerated carbonation and then immersed in NaCl solution to study the effect of carbonation on chloride ingress. The penetration depth of chloride ion in fly ash mortar immersed in NaCl solution was found to be larger at an early age, but later became almost the same as that of the mortar without fly ash. The depth of carbonation of mortar cured in NaCl solution was found to be smaller than that in distilled water and the same trend was observed independent with initial curing time and the addition of fly ash. Fly ash mortar showed higher depth of carbonation than the control mortar. The corrosion potential of the steel reinforcement was found to be affected by both the chloride penetration and carbonation.

91. Nolan, J.L. and R.H. Atkinson (1983). **Evaluation of Brick Masonry by Non-Destructive Methods.** *Strengthening of Building Structures - Diagnosis and Therapy,* IABSE Symposium, Venezia, Vol. 46, pp. 85-92.

The authors present an investigation of various non-destructive testing methods and their potential application to masonry. The various non-destructive technique test results were correlated to mechanical properties such as compressive strength, modulus of rupture and shear strength. The techniques were evaluated in terms of how well they could predict the mechanical properties. Although the study was inconclusive, certain methods appeared to have potential as practical means of evaluating masonry strength. The Schmidt Rebound Hammer and the ultrasonic pulse velocity were more closely related to the compressive strength and modulus of rupture, respectively. None of the techniques seems to be able to predict joint shear strength.

92. Oelsner, G. (1982). **Atmospheric Corrosion Testing in the Federal Republic of Germany.** in *Atmospheric Corrosion,* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 797-805.

The results of field tests for 12 different aluminum alloys under atmospheric conditions for a period of ten years are presented. In general the material loss due to corrosion and pitting depth were found to be more severe on the specimens inclined at 45° than the vertical test specimens. The underside of the inclined test specimens were found to corrode more than the vertical specimens. Anodized and polished samples were also tested. The samples placed in an industrial atmosphere were found to corrode more than those placed in a coastal area. The correlation between the composition of the atmosphere and the observed corrosion was not studied in this work.

93. Ohta, T. (1991). **Corrosion of Reinforcing Steel in Concrete Exposed to Sea Air.** in *Durability of Concrete,* Second International Conference, Montreal, ACI SP-126, Vol. 1, pp. 459-477.

Long term exposure test results of reinforced concrete beams are reported. Test samples were exposed to sea air for 2 to 20 years. The parameters were thickness of concrete cover, type of cement, cement content, and crack width. The type of cement had a great influence on the depth of chloride penetration. The diffusion coefficient of chloride ion was found to be 3-4 times lower in blended cements than in ordinary portland cement. The thickness of the concrete cover was found to have a very important effect on the corrosion protection of reinforcing steel. The influence of crack width was found to be negligible for thin concrete covers whereas it had some influence on the corrosion for thick concrete covers (40 mm). The use of epoxy coating on the surface of the concrete was found to be effective in reducing corrosion of the reinforcing steel.

94. Ohtsu, M. and K. Yuno (1991). **Development of In-Situ Nondestructive Evaluation (NDE) Techniques for Rebar Corrosion, Concrete Deterioration and Internal Cracks.** in *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design.* Proceedings ACI International Conference, Hong Kong, ACI SP-128, Vol. II, V.M. Malhotra, Editor, pp. 893-907.

    The authors present in situ nondestructive techniques for estimating rebar corrosion, crack depth, deterioration due to microfracturing, and kinematics of crack nucleation in concrete structures. An improved half-cell potential technique is presented for monitoring of rebar corrosion. The depth of surface crack is evaluated by ultrasonic spectroscopy. The amount of microcracks associated with the deterioration is estimated from acoustic emission activity during a uniaxial compression test of core sample.

95. Oldfield, J.W. and B. Todd (1990). **Ambient-Temperature Stress Corrosion Cracking of Austenitic Stainless Steel in Swimming Pools.** *Materials Performance*, Vol. 29, No. 12, pp. 57-58.

    The authors report instances of stainless steel SCC when exposed to swimming pools atmosphere. Although it is generally accepted that SCC of SS does not occur at temperatures below 60 °C, several cases of failure in ambient environment around swimming pools have been reported. The Nickel Development Institute, studying the problem, has demonstrated that SCC of austenitic SS can take place at room temperature in chloride solutions of very low pH. Such condition however, does not seem to prevail in the environments where failures by SCC took place. Until the mechanisms of attack are clarified, use of type 304 and 316 (titanium stabilized) stainless steel for stressed components exposed to swimming pool atmospheres cannot be recommended.

96. Papadakis, V.G., M.N. Fardis, and C.G. Vayenas (1990). **Fundamental Concrete Carbonation Model and Application to Durability of Reinforced Concrete.** in *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 27-38.

    The physicochemical processes of concrete carbonation are modeled mathematically. The purpose of the work was to cover some of the shortcomings of empirical carbonation models developed by other researchers. The mathematical model was used to predict the carbonation front with respect to cement paste composition and environmental conditions. A good correlation between laboratory results and prediction from the mathematical model was observed.

97. Philipose, K.E., R.F. Feldman, and J.J. Beaudoin (1991). **Durability Predictions from Rate of Diffusion Testing of Normal Portland Cement, Fly Ash, and Slag Concrete.** In *Durability of Concrete*, Second International Conference, Montreal, ACI SP-126, Vol. 1, pp. 335-354.

    The authors present the results of research in progress to establish the diffusion rates of chlorides and sulfate ions. The research program has for its first objective the qualification of a concrete with a minimum service life of 500 years used for nuclear waste containment. Fly ash and slag systems (i.e. addition of fly ash and slag) indicated superior resistance to ionic ingress, and a decrease in water-to-cement ratio enhances the resistance even further. The slag system seemed to have the highest resistance to ionic ingress. The rate of ingress of chloride ions appeared to be diffusion controlled. The decrease in chloride content with depth of ingress was found to be more rapid with slag systems than others. The rate of ingress of sulfate ions was found to be considerably lower than chloride ions for all systems. Linear regression analysis of the limited data was used to predict the depth of penetration of the chloride ions in 500 years.

98. Raharinaivo, A., P. Brevet, G. Grimaldi, and G. Pannier (1986). **Relationships Between Concrete Deterioration and Reinforcing Steel Corrosion.** *Durability of Building Materials*, Vol. 4, No. 2, pp. 97-112.

    An investigation of the influence of crack geometry on concrete reinforcement corrosion is presented. Tests on reinforced mortar specimens were performed to show the effect of the cement-paste deterioration on the reinforcing steel corrosion. Tests on reinforced concrete specimens were conducted to determine the effect of aggregates on the diffusion of aggressive ions through the concrete. The specimens were cracked after preparation by subjecting the specimens to bending. Corrosion conditions were monitored during the tests using electrode potential measurements. The crack opening was found to have the greatest influence on steel corrosion for a given cover thickness. Corrosion of the steel in the samples was concentrated in the regions close to cracks.

99. Rasheeduzzafar, F.H. Dakhil, M.A. Bader, and M.M. Khan (1992). **Performance of Corrosion Resisting Steels in Chloride-Bearing Concrete.** *ACI Materials Journal*, Vol. 89, No. 5, Sept. - Oct., pp. 439-448.

Bare mild, galvanized, epoxy-coated, and stainless clad reinforcing steels have been evaluated in a 7-year exposure site program for corrosion resistance performance in chloride-bearing concretes. The parameters investigated were the type of reinforcing steel and the chloride content. The test specimens consisted of concrete prisms with embedded rebars. The bare steel and the galvanized steel performed rather poorly in the test. The level of chloride in the mix was found to have a significant influence on the corrosion of the bare and galvanized steel. The corrosion rate was found to be greater in the concretes with the highest chloride contents. Epoxy coated rebars have corroded only in the specimens with the highest chloride content. The stainless clad reinforcing steel showed no sign of corrosion over the 7 year period. Several references on corrosion of galvanized steel in concrete are presented.

100. Roper, H. and D. Baweja (1991). **Carbonation-Chloride Interactions and Their Influence on Corrosion Rates of Steel in Concrete.** *Durability of Concrete*, Second International Conference, Montreal, ACI SP-126, Vol. 1, pp. 295-315.

The authors present the results of an investigation of corrosion of reinforcing steel subjected to the combined effect of a chloride environment and carbonation of concrete. Studies on interrelationships between carbonation and chloride ion ingress showed that carbonation rates increase with increasing water/cement ratios. Replacement of cement by fly ash did not detrimentally affect the carbonation resistance of concrete and the addition of chloride ions to the concrete mixes tended to reduce the carbonation of fly ash concretes. Potentiodynamic anodic polarization testing of corroding reinforcement revealed that both carbonation and chloride ion concentration increase corrosion rate. It was found that corrosion caused by carbonation increased with increasing chloride concentration provided that the carbonation rate was itself not retarded by the presence of chlorides. This leads to the conclusion that corrosion rate is significantly influenced by complex interactions due to the presence of carbon dioxide and chloride ions.

101. Rostam, S. (1989). **Influence of Material Properties on the Durability of Structure.** in *Durability of Structures*, IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/1, pp. 125-136.

The influence of material properties on the durability of structures is an integrated part of the interaction between environmental aggressivity and the resistance of the structure. Durability is treated in a Service Life concept. The service life achieved depends on initial decisions, codes and standards and on management and maintenance systems employed. The design of new structures is guided by codes and standards. The CEB-FIP Model Code 1990 is the first Service Life Code and helps bridge the communication gap existing between the material scientists and the structural engineers.

102. Saricimen, H., A.J. Al-Tayyib, M. Maslehuddin, and M. Shamim (1991) **Concrete Deterioration in High Chloride and Sulfate Environment and Repair Strategies.** In *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design*, Proceedings ACI International Conference, Hong Kong, V.M. Malhotra, Ed., Vol. 1, ACI SP-128, pp. 19-33.

The authors claim that standards of practice of reinforced concrete in temperate regions are inadequate for the climatic conditions existing in Saudi Arabia. Observations from field inspection of deteriorated underground electrical power manholes and sea water cooling canals are reported. The concrete cover provided is reported as a nominal value only. Chloride penetration measurements performed in a lab show that an extremely high chloride content exists 60 mm below the surface. The pH of the deteriorated concrete was from 12.6 to 13.2, indicating insignificant carbonation in the concrete. The authors did not report the strength of the concrete, the salt content of the aggregates used in the concrete, and the permeability of the concrete. (It is quite common in the middle east countries to use aggregates containing significant amounts of chlorides. This could explain the high concentration of chlorides measured in the field samples. Poor quality concrete resulting from a high w/c ratio would also be reflected by a low strength and high permeability. The authors failed to report the relevant information which could have pointed out either the inadequacy of foreign standards of practice for the middle east countries or the generally poor quality control exercised in the middle east countries).

103. Sarkar, S. L., S. Chandra and M. Rodhe (1992). **Microstructural Investigation of Natural Deterioration of Building Materials in Gothenburg, Sweden.** (refer to Case Studies)

104. Sereda, P.J. (1969). **Performance of Building Materials.** Canadian Building Digest, Division of Building Research, National Research Council of Canada, CBD 115.

Durability is viewed as a basic property of the materials which can be measured as the length of time it will serve satisfactorily. Durability, or service life, must always be related to the particular conditions involved.

Materials react with their environment because of their chemical and physical and mechanical nature. It is its chemical nature that determines the reactivity of a material to other materials and to some elements of the environment. To understand the physical and mechanical response of a material we must think of the material in terms of its microstructure. In that respect we can differentiate between non-porous materials (metals, ceramics, polymers) and porous materials which offer more surface of contact with the atmosphere. The environmental factors which influence the performance of materials are briefly presented. Those are: temperature (the temperature inside the material rather than the air temperature must be considered), moisture content and its cycling, ultraviolet light which can affect the molecular bonds in organic materials, and gases, liquids, bacteria and other life forms. Various chemical and physical processes which affect the service life of materials are introduced such as aging, efflorescence, frost action, wetting and drying and chemical attack.

105. Skerry, B.S., J.B. Johnson, and G.C. Wood (1988). **Corrosion in Smoke, Hydrocarbon and SO_2 Polluted Atmospheres - I. General Behaviour of Iron.** *Corrosion Science*, Vol. 28, No. 7, pp. 657-695.

The effect of atmospheric pollutants on the corrosion characteristics of iron foil specimens is presented and discussed. The results of laboratory tests under controlled atmosphere have shown that: 1) sulfur dioxide significantly enhances corrosion in air; 2) smoke enhances corrosion in air; 3) the effect of ethane and acetylene in air is only marginal while ethylene has no apparent effect; 4) smoke worsens the effect of sulfur dioxide but sulfur dioxide appears to have the overall controlling influence; 5) ethane greatly enhances the effect of sulfur dioxide and smoke. The morphological effect of SO_2 was the change from relatively localized attack to complete coverage by corrosion products. Other interaction effects between the various pollutants have been observed. The authors present interesting discussions of the effects observed in the laboratory in terms of the chemical activity taking place on the surface of iron and the appearance of the corrosion products. Chemical processes taking place during corrosion of iron in the presence of atmospheric pollutants are proposed.

106. Skerry, B. S. , J.B. Johnson, and G.C. Wood (1988). **Corrosion in Smoke, Hydrocarbon and SO_2 Polluted Atmospheres - III. The General Behaviour of Zinc.** *Corrosion Science*, Vol. 28, No. 7, pp. 721-740.

Tests were performed on specimens of zinc foil exposed to various environments. Specimens were exposed in a modified industrial atmosphere test chamber to an air-based environment at 298 °K with a relative humidity of 85% and a CO_2 concentration of 5500 ppm. Additions were made of SO_2, ethane, ethylene and acetylene and smoke. SO_2 was found to have a large and steadily increasing corrosion enhancement effect. Smoke was lightly corrosive to zinc and also promoted to some extent corrosivity in the presence of SO_2. Smoke in the presence of SO_2 represented the most corrosive test environment. Hydrocarbons only affected zinc corrosion marginally. However, when combined with SO_2 or smoke, hydrocarbons were found to affect significantly the corrosion process. Hydrocarbons were found to have an inhibiting or enhancing effect. The effects of smoke and some hydrocarbons are considered to be due to factors such as sorption, catalytic activity, interaction with moisture.

107. Southwell, C.R. and J.D. Bultman (1982). **Atmospheric Corrosion Testing in the Tropics.** in *Atmospheric Corrosion.* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 943-967.

The authors discuss corrosion testing of bare metals at various tropical locations and attempt to evaluate the relative corrosiveness of different tropical atmospheres where temperatures and relative humidities can be significantly greater than for temperate regions. The authors present a brief review of the work performed on tropical corrosion since the early 1950's. They also report on exposure studies conducted by ASTM at U.S. Naval Research Laboratory in Panama. The work included 54 metals and alloys among which 6 were pure metals, 24 were ferrous metals, 20 were non-ferrous alloys, and 4 were non-ferrous-coated steels. Two exposure sites were utilized: a site located 8 km inland from the pacific ocean in a semiurban location, and a marine site located near the Atlantic ocean. Limited exposure sites were also set at two other locations. Exposure periods were for 16 years. Tension tests were also run on the exposed specimens to determine any change in strength that might have taken place with corrosion. Although not very conclusive, the tensile tests on steel showed that the reduction in strength is directly proportional to the loss in cross-section area due to corrosion. Although the corrosion rates at the inland site were much lower than for the marine site during the first two years, the difference was significantly smaller on the long-term. The stabilized corrosion rates were used as a basis of comparison. The tropical open inland sites showed corrosion losses equal to or slightly higher than the U.S. rural site in Pennsylvania. The authors also present the result of galvanic corrosion obtained from coupling dissimilar metals.

108. Spence, J.W. and F.H. Haynie (1988). **Theoretical Damage Function for the Effects of Acid Deposition in Galvanized Steel Structures.** Environmental Protection Agency, EPA/600/S3-88/027.

The authors present the development of a theoretical damage function for the prediction of the corrosion of galvanized steel structures by wet and dry deposition. The function was developed from thermodynamics and kinetics of atmospheric corrosion chemistry. The function expresses the corrosion rate of zinc in terms of the competing rate of build up and dissolution of the protective zinc carbonate with exposure time. The principal findings of the theoretical analysis are : SO_2 on the surface (either from dry or wet deposition) reacts stoichiometrically (reaction is proportional to the amount of SO_2 present) with zinc during periods of surface wetness; rain acidity reacts stoichiometrically with the zinc (reaction is proportional to the amount of dissolved H^+ in rain); the corrosion film of zinc carbonate is soluble in clean rain and the dissolution depends on the residence time of the rain on the surface; deposition velocity controls the rate of corrosion of galvanized steel structures by gaseous SO_2 during periods of wetness. Lab and field tests are in progress to evaluate the theoretical damage function.

109. Swamy, R.N. and S. Tanikawa (1991). **Control of Steel Corrosion in Chloride Contaminated Concrete through ARON WALL Surface Coating.** In *Durability of Concrete*, Second International Conference, Montreal, Canada, ACI SP-126, V.M. Malhotra, Ed., Vol. 1, pp. 371-391.

The authors present data on the performance of an acrylic rubber coating called ARON WALL in a corrosive environment. The information presented in this paper is essentially the same as the information presented in the paper summarized below.

110. Swamy, R.N. (1990). **In-Situ Behaviour of Galvanized Reinforcement.** *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 Nov., pp. 299-312.

The author addresses the considerable controversy which exists with regard to the performance of galvanized rebars in reinforced concrete. While some studies show substantially improved durability over uncoated steel bars, others appear to indicate slightly better, equal, or sometimes even worse performance. In general, while some field and laboratory test results show that zinc coated reinforcement does not perform well , field experience contradicts such evaluations. Tests have shown that in dilute NaOH the minimum corrosion rate of zinc occurs at a pH of about 12.5. However, there seems to exist a threshold pH of 13.35±0.10 which defines the onset of active corrosion in galvanized steel. Although pore solution studies have shown that pore solution pH can exceed the threshold value, cores taken from structures exposed to the ambient environment show pH values less than the critical threshold value, providing a stable environment for galvanized steel. The author believes that the test solutions used for laboratory experiments are not representative of the pore solution found in concrete exposed to the atmosphere. Tests have shown that, as opposed to black steel which shows an increased rate of corrosion in carbonated concrete, the zinc coating on galvanized steel remains passive in carbonated concrete. By correlation between lab and field tests the author concludes that galvanized/chromated bars have excellent corrosion resistance in concrete with high levels of chloride. The author presents interesting references on corrosion of zinc and galvanized steel in concrete.

111. Swamy, R.N. and S. Tanikawa (1991). **A Highly Elastic Surface Coating to Protect Structures Exposed to Coastal/Marine Environments.** In *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design*, Proceedings ACI International Conference, Hong Kong, V.M. Malhotra, Ed., Vol. 1, ACI SP-128, pp. 1-18.

The authors present data on the performance characteristics of a highly elastic acrylic rubber coating called ARON WALL coating. The coating consists of a primer (chlorinated resin), a base coat (soft monomer) and a top coat (acrylic resin, acrylic urethane resin, or acrylic silicone resin) for an overall thickness of 1.1 mm. The coating was tested for its ability to bridge cracks, fatigue resistance, weathering resistance, resistance to ozone, U.V. ray exposure, temperature resistance, adhesion strength, carbonation depth, and chloride penetration. The coating showed a good performance in all areas. It should be noted that the maximum time of exposure to outdoor atmosphere is 10 years. Seventeen references on the performance and use of various surface coatings are presented.

112. Timmins, F.D. (1974). **Protection of Steel - Paint, Metal Spray, Hot Dip Galvanize, Weathering Steel - Which and Why?** Welding Institute, Seventh International Metal Spraying Conference, London, September, Vol. 1, pp. 232-244.

The author reviews the various protection systems listed in the title. The use of metal spraying is strongly favored over the other protection systems. The complexity of the paint systems and the lack of quality control generally encountered during their application is the basis for the rejection of the paint systems. Hot dip galvanizing is rejected based on the difficulty to get other coatings to adhere to the zinc coating, the low resistance of zinc to corrosion in highly polluted areas and the potential heat related problems encountered during the hot dip galvanizing process. Weathering steels show low resistance to corrosion in wet environments. Aluminum spray followed by painting is said to provide the best protection. (Notes: It is fundamentally correct that metal spraying followed by paint coating provides a very good protection from corrosive environments. However, this does not provide a basis for rejection of other protection systems. It is the writer's opinion that the best protection system is the cheapest system which will adequately protect the structure in the specific environment where the structure is intended to be used. For this reason some cheaper and maybe less performing systems are preferred in mildly corrosive environments.)

113. Tolstoy, N., G. Andersson, C. Sjöström, and V. Kucera (1990). **Statistical Field Survey of Exterior Building Materials Degradation.** (refer to Case Studies)

114. Tuthill, L.H. (1991). **Long Service Life of Concrete.** *Concrete International,* Vol. 13, No. 7, pp. 15-17.

The author discusses some of the aspects to consider if a long service life is to be obtained from concrete. Coarse aggregates should be chosen by uniformity of grading and minimum variation of the percent of significant undersize. In most cases normal portland cement can be used except in those rare cases where sulfates may be present or when the most favourable aggregates for a project contain alkali-reactive elements. The addition of pozzolans is recommended for reduced permeability (use of silica fume) or to reduce the heat of hydration in massive structures. The importance of good curing is also emphasized.

115. Tuutti, K. (1982). **Corrosion of Steel in Concrete.** Swedish Cement and Concrete Research Institute, CBI Research, fo 4.82.

This report is the most complete and detailed research report on corrosion processes of reinforcement in concrete. The process of corrosion is illustrated with a schematic model where the service life is divided into a period of initiation and a period of propagation of corrosion. Theoretical models have been proposed to estimate the time of initiation from the flow of penetrating substances into the concrete cover and the attainment of a threshold concentration. The rate of corrosion in the propagation period has been defined in terms of the moisture content of the concrete and temperature. Different models for this stage have been proposed depending on the initiation mechanism. The final stage of corrosion, cracking of the concrete cover and reduction of the steel cross-sectional area is discussed in the model. The author also presents a method for service life prediction and comparison with laboratory investigations.

116. Tuutti, K. (1980). **Service Life of Structures with Regard to Corrosion of Embedded Steel.** *Performance of Concrete in Marine Environment,* Publication SP-65, American Concrete Institute, pp. 223-236.

The service life of concrete structures with regard to reinforcement corrosion is broken down into an initiation stage and a propagation stage. The initiation stage is characterized by the carbonation of the concrete cover and/or the ingress of chloride ions in the concrete. The author discusses the factors affecting the rate of carbonation and the rate of chloride ingress in the concrete. During the propagation stage active corrosion of the reinforcing steel is taking place. Two factors are considered to be important in that stage, namely, the electrolyte, which establishes the contact between anode and cathode surfaces, and oxygen, which must be supplied to the cathode if the reactions are to proceed. The service life is taken as the time to develop visible cracks in the concrete cover (0.1 mm) since the corrosion rate at that time is greatly increased by the flow of oxygen in cracks.

117. Wolf, J. and Lahnert, B. (1990). **Performance of Latex-Modified Thin-Set Mortars in Applications of Thin-Brick Veneer.** *Serviceability and Durability of Construction Materials.* Proceedings of the First Materials Engineering Congress, Denver, CO., Aug. 13-15, Vol. 1, pp. 508-516.

The paper discusses the application specifications and procedures for thin brick. Latex modified mortars are used to increase adhesion to the building facade and to the thin brick. In all the failure cases investigated by the authors it was found that the application had not been done in accordance to the manufacturer's specifications. Poor bond between the substrate and the mortar was found to be the primary reason for failure

by debonding. Inadequate hydration of the mortar near the substrate was found to be at the origin of the poor bond. Wetting of the substrate has been recommended by ANSI 108.5 prior to the application of the substrate. Grouting of the joints along with strict quality control was recommended. Grouting of the joints provides additional support to the thin bricks.

118. Wright, J.R. and G. Frohnsdorff (1985). **Durability of Building Materials : Durability Research in the United States and the Influence of RILEM on Durability Research.** *Materials and Structures / Matériaux et Constructions,* Vol. 18, No. 105, May-June, pp. 205-214.

The paper reviews some of the research on the durability of building materials which has been carried out at the US National Bureau of Standards and other US laboratories in the recent years. It also draws attention to the role of RILEM in promoting international collaboration in research on the durability of building materials. In 1978 an ASTM building materials standard of a new type was established. The standard formalized the logic of accelerated testing and indicated the steps which should be taken in setting up credible tests for service life prediction. Using the methodology outlined in the standard NBS developed an approach to service life prediction of protective coatings for steel. NBS has explored the possible application of infrared thermography and the pulse echo technique to detect flaws in seams of single-ply roofing membranes. The Forest Products Laboratory is concerned with the performance and protection of wood. Research is under way to find wood preservatives which are more environmental acceptable. Organizations which have been major contributors to research on concrete durability for many decades include the US Army Waterways Experiment Station, the Bureau of Reclamation, and the Portland Cement Association. The initial research on epoxy coatings for protection of reinforcing steel against corrosion was carried out by NBS in the 1970's. The importance of the establishment of feedback systems which can capture the information from those responsible for the maintenance, repair and rehabilitation of facilities is emphasized. The areas where research is needed have been identified as: development and application of techniques for elucidating the degradation mechanisms; characterization of environments (including microclimates); probabilistic mathematical modeling of degradation; service life prediction; condition assessment of materials in existing structures; and construction of large data bases with evaluated data.

119. Yeomans, S.R. (1991). **Comparative Studies of Galvanized and Epoxy Coated Steel Reinforcement in Concrete.** In *Durability of Concrete,* Second International Conference, Montreal, Canada, ACI SP-126, V.M. Malhotra, Ed., Vol. 1, pp. 355-370.

Black steel, galvanized steel and epoxy coated steel rebars were tested under a salt fog environment and under wet and dry conditions. Half cell potential measurements were made to assess the state of corrosion of the test specimens. Two series of tests, consisting of rebars embedded in concrete cylinders of different sizes, were conducted. In both series the black steel specimens performed badly showing early signs of corrosion. In the first series of tests the epoxy coated rebars performed well with no sign of corrosion after 142 days. However, the galvanized rebars showed early signs of zinc corrosion (half cell potential of -1050 mV). The potential of the galvanized bars slowly changed as the zinc coating depleted. At the end of 142 days the zinc was still providing protection. In the second test series the ends of the rebars were left unprotected. Early corrosion of the epoxy coated rebars was detected where the coating had been damaged. However, the zinc coating on the galvanized rebars protected the exposed steel surfaces adequately. The bond strength of galvanized and epoxy coated deformed rebars was found the be the same as that for the black steel. However, for plain reinforcement, the ultimate bond strength of the epoxy coated steel is 17% less than that of black steel, while the weathered galvanized steel is 31% higher.

Environment

1. Anon. (1993). **Removing Chloride Ions from Reinforced Concrete.** *Concrete Repair Digest*, February/March, pp. 11-14.

This article is based on an earlier paper by D.G. Manning and F. Pianca of the Ontario Ministry of Transportation. It reports the results of an investigation by the OMT on a technique to remove chloride ions from concrete. The technique consists of applying an anode to the surface of a reinforced concrete structure and passing current between the anode and reinforcing steel, which acts as the cathode. Since chloride ions are negatively charged, they are pulled toward the positively charged anode. The anode is temporary and the current density applied is about 100 times that used in most cathodic protection systems. The system was maintained in place for 8 weeks and the cellulose fibers used to cover the anode is kept wet during the treatment. The results of a test on a bridge pier have shown that the chloride concentration is effectively reduced to a depth equal to the concrete cover. Corrosion activity was also found to have been reduced significantly to a passive level. The effectiveness of the method however is uncertain when chlorides penetrate deeper than the concrete cover. It is possible that the chlorides in the concrete beyond the steel reinforcement will not be removed since they may not be able to move past the negatively charged cathode. The cost effectiveness of the technique still needs to be assessed.

2. Arya, C. and J.B. Newman (1990). **Problem of Predicting Risk of Corrosion of Steel in Chloride Contaminated Concrete.** *Proceedings of the Institution of Civil Engineers*, Part 1, Vol. 88, Oct., pp. 875-888.

The authors examine three different approaches to measure the chloride content in concrete. The three techniques measure different levels of chloride: the total chloride content (acid-soluble), the water-soluble chloride content, and the chloride/hydroxyl ion concentration ratio in the pore solution. It is shown that, although the total chloride content can be determined readily, it may be a poor indicator of corrosion risk since no allowance is made for mix composition or source of chloride contamination. The water-soluble chloride content may be an inappropriate parameter to relate to corrosion risk since it provides only an approximation to the free chloride content over a limited range of mixes. The free chloride/hydroxyl ion ratio is a more realistic indicator of corrosion risk, but there are difficulties associated with its determination in actual structures. An alternative procedure is proposed whereby the free chloride content is measured by way of total chloride, using empirical relationships derived from results obtained by laboratory extraction of free chloride.

3. Asakura, S., M. Moriyama, and M. Matsumoto (1991). **A Study on the Distribution of Salt Concentration in the Atmosphere at Coastal Areas.** *Energy and Buildings*, Vol. 16, Nos. 3-4, pp. 1069-1077.

The authors present the result of measurements of salt concentration in the atmosphere as a function of distance from the coastline and height. The field measurements showed that the chlorine concentration reduced with increasing distance from the coastline. The variation with height showed that a maximum concentration exists at some height above the ground surface (about 12 m). The lower concentration near the ground is believed to be caused by the absorption of the chlorine by the soil. The results of numerical calculations of salt concentration are also presented. The calculated vertical concentrations were found to be in good agreement with the measured values. However, the calculated horizontal distribution of the concentration was found to be lower than the measured distribution.

4. Ashton, H.E. (1970). **Irradiation Effects on Organic Materials** (refer to Materials)

5. Ashton, H.E. (1970). **Radiation and Other Weather Factors.** Canadian Building Digest 122, National Research Council of Canada, Ottawa, February.

The digest discusses how radiation affects organic building materials when its action is associated with the action of water and oxygen. Because the severity of the attack is increased with exposure to more than one agent, preventive action must be taken to reduce degradation. The author discusses in particular the use of polymers unaffected by UV. The polymers may be formed with molecules which possess chemical bonds resistant to UV attack such as silicone polymers which have a silicone oxide backbone with organic side groups. Incorporation of compounds that reflect or absorb UV is another alternative. The latter, called UV absorbers, must be able to reflect the visible light (for clear polymers) and absorb UV light. Carbon black is effective at absorbing UV light but its colour is not always desirable. UV absorbers must also be able to resist degradation from UV light by dissipating the energy harmlessly as heat. The digest presents a good introduction to deterioration of polymers.

6. Ashton, H.E. and P.J. Sereda (1982). **Environment, Microenvironment and Durability of Building Materials.** *Durability of Building Materials*, Vol. 1, No. 1, pp. 49-65.

The authors attempt to demonstrate that the microenvironment defines the precise conditions of solid materials and the immediate layers of liquid or gas prevailing at the site where chemical or physical processes of deterioration are taking place. It emphasizes the importance of measuring the conditions of the

microenvironment as a guide to the direction of future studies and investigations. The authors show that short-term movement of building components is predictable from surface temperature data but not from ambient temperature data. Surface moisture, defined as the time-of-wetness, can be monitored to provide the reaction time for corrosion and surface deterioration processes. The paper identifies the need to monitor the total deposition of pollutants on the surface of materials in service.

7. Atteraas, L. and S. Haagenrud (1982). **Atmospheric Corrosion in Norway.** (refer to Materials)

8. Baker, A.J. (1980). **Corrosion of Metal in Wood Products.** (refer to Materials)

9. Barneyback, R.S. Jr., and S Diamond (1981). **Expression and Analysis of Pore Fluids From Hardened Cement Pastes and Mortars.** *Cement and Concrete Research*, Vol. 11, No. 2, pp. 279-285.

   The authors describe an apparatus that has been used for expression of pore solution from hardened portland cement pastes and mortars. Particulars with respect to the design, fabrication, and operation of such equipment are given,. Methods for the analysis of the resulting small volumes of pore solutions are discussed. Although questionable, it is believed that the composition of the pore solutions obtained are representative of that of the bulk of the pore solution within the paste or mortar from which the solutions have been obtained.

10. Barton, K., D. Knotkova, P. Strekalov, V. Kemhadze, V. Kozhukharov, A. Sobor, M. Zaydel, and T. Bestek (1980). **Atmospheric Corrosion of Metallic Systems II. Analysis of the Corrosion Aggressiveness of the Media at the Atmospheric Testing Stations of Member-Nations of COMECON, According to the Results of Five-Year Tests on Steel, Zinc, Copper, and Aluminum** (refer to Materials)

11. Benarie, M. and F. L. Lipfert (1986). **A General Corrosion Function in Terms of Atmospheric Pollutant Concentrations and Rain pH.** *Atmospheric Environment*, Vol. 20, No. 10, pp. 1947-1958.

    The atmospheric corrosion of metals has been described by a linear bi-logarithmic function of the form $M = at^b$ where a and b are constants determined by analysis of test results. The constant a was expressed in terms of the time of wetness and the SO_2 and Cl^- deposition on the surface. The exponent b, which was found to characterize the diffusivity of the corrosion product layer was expressed in terms of the rain pH. Although the simple exponential model worked well with the results obtained by various investigators, it is, however, not a complete solution because it does not take into account all the complexities of the corrosion process. The value of b in the model was found to be closely correlated to the rain pH for the results obtained on zinc, but the correlation was less clear for the steel samples. It is believed that the differences between the steel samples used by various investigators is at the origin of the lack of correlation observed for steel.

12. Berke, N.S. (1991). **Corrosion Inhibitors in Concrete.** (refer to Materials)

13. Brown, P.W. and L.W. Masters (1982). **Factors Affecting the Corrosion of Metals in the Atmosphere.** (refer to Materials)

14. Building Research Establishment (1985). **Corrosion of Metals by Wood.** (refer to Materials)

15. Carlson, A.R. (1991). **Computer Simulation of Wall Condensation Problems.** *Water in Exterior Building Walls: Problems and Solutions*, ASTM STP 1107, T.A. Schwartz, Ed., American Society for Testing and Materials, pp. 210-228.

    The author presents cases of field investigation of moisture condensation problems in exterior walls. A computer analysis on spreadsheet is presented whereby moisture condensation problems inside walls can be predicted from measured relative humidity and temperature on either sides of the wall and thermal and vapour penetration characteristics of the building materials. The importance of a good vapour barrier is demonstrated. It appears that a 6 mil polyethylene is one of the better vapour retarders. The importance of proper ventilation and moisture control inside air-tight houses is also emphasized.

16. Carter, J.P., P. J. Linstrom, D. R. Flinn, and S. D. Cramer (1987). **The Effects of Sheltering and Orientation on the Atmospheric Corrosion of Structural Metals.** (refer to Materials)

17. Chawla, S.K. and J.H. Payer (1990). **Atmospheric Corrosion: Comparison of Indoor vs. Outdoor.** *Innovation and Technology Transfer for Corrosion Control.* 11th Internantional Corrosion Congress, Florence, Italy, April 2-6, Vol. 2, pp. 2.17-2.24.

The authors discuss the differences between indoor and outdoor environments with respect to atmospheric water, atmospheric ionic sources (CO_2, SO_2, HCl, NO_x), atmospheric catalysts (Fe and Mn) and solar radiation. They provide a table with normal ranges of the various factors both in indoor and outdoor environments. The values presented were obtained from various cited references. The effect of the environments (both indoor and outdoor) on the corrosion rate of copper are then discussed. The paper is a good source of information for the nature of the atmospheric factors influencing the corrosion of metals.

18. Cole, I.S. (1993). **Wall Cavity Microclimate and Material Durability Parameters – An Australian Survey.** 6th International Conference on Durability of Building Materials and Components, Japan, 25-28 October.

The results of microclimate monitoring in wall cavities of three houses in Australia are presented. The houses were located across three Australian climatic zones, namely, tropical, sub-tropical and temperate. The houses were brick veneer with tile roofs, typical of Australia. Temperature and relative humidity were monitored in a sheltered and in an exposed wall cavity. An analysis of the calculated absolute humidity in the cavities exposed to the rain indicated that there was possibility for rain penetration. A study of the time-of-wetness (using ISO definition of time during which RH>80% while above freezing) was performed. Comparison of the time-of-wetness inside the wall cavities with outdoor conditions indicated that there is little correlation between the two. The TOW within the cavities fluctuated less but the conditions were found to be potentially more severe than outdoor and potential corrosion problems were observed. An equilibrium moisture content (EMC) was estimated from measured RH and temperature. Wood decay and deterioration of adhesives were the factors being investigated. It was found that the EMC was above 20% long enough to cause potential problems of wood decay. Guidelines from UK and US were used to estimate whether problems existed w.r.t. adhesives deterioration. It was found that potential problems existed according to U.S. codes but not according to U.K. code which is somewhat less stringent than the U.S. code. No description of the instrumentation and their location is given.

19. Cole, I.S. (1992). **Corrosion in Wall Cavities – Occurrence, Conditions and Prevention.** Second National Masonry Seminar, Melbourne, Australia, November.

The problem of corrosion of metallic components in wall cavities is believed to be a widespread phenomenon. Evidence of the serious nature of the problem in Australia was discovered after the Newcastle earthquake which, although small, caused a lot of damage. Part of the problem was found to be corrosion of the wall ties. The author reports the results of a monitoring program (this is also reported in Cole (1993) above) which indicated that the moisture conditions inside the cavity of exposed walls were favorable to corrosion activity during a significant portion of the time. A short discussion of potential problems with embedded components is given. It is not known whether wind driven rain can cause increased corrosion of embedded components in mortar joints. The author concludes with a brief discussion of corrosion prevention by proper drainage of cavities, reduction of moisture ingress and use of corrosion resistant materials (stainless steel, brass, galvalum, or increased zinc thickness).

20. Cole, I.S. (1992). **Newcastle Earthquake and Cavity Corrosion: Implications for the Rest of Australia.** 14th Annual Conference of the Australian Building Surveyors Queensland Chapter, October, Gold Coast Australia.

This paper presents the same material as the above two papers by the same author. In the discussion the author states that the rate of corrosion of copper and steel exposed to the open atmosphere in Australia is comparatively the same as that measured in the U.K. It is therefore believed that the same problems of corrosion in the wall cavities can be expected in both countries. Also comparison of conditions in Newcastle with those elsewhere in Australia indicate that corrosion problems which lead to unsafe masonry structures can exist throughout Australia.

21. Comité Euro-International du Béton (1989). **Durable Concrete Structures - CEB Design Guide.** CEB Bulletin d'Information No. 182, Second Edition.

The Comité Euro-International du Béton provides a design guideline for durable concrete. The guide provides a theoretical background to concrete deterioration (corrosion of steel in concrete, causes of concrete cracking, and transport mechanisms in concrete). Processes of deterioration of concrete (physical (in the form of cracking, frost and de-icing agents, erosion), chemical (acid, sulphate, and alkali attacks) and biological) are discussed. The mechanisms of protection and deterioration of steel in concrete and the effect of corrosion are also discussed. Recommendations are given for the classification of the environments, design, construction and maintenance of concrete structures, and protection measures for the concrete and the steel reinforcement.

22. Costa, J.M. and M. Vilarrasa (1987). **Corrosion Mapping for Catalonia, Spain.** Proceedings of the 10th International Congress on Metallic Corrosion, Vol. 1, pp. 35-44.

Results of three-year tests of atmospheric corrosion of carbon steel, copper, aluminum, zinc, brass and stainless are reported. The test specimens were standard plate specimens. The tests were conducted at 42 exposure sites across Catalonia. Weight loss and atmospheric factors such as temperature, relative humidity, SO_2 and Cl^- concentration in the air were measured. The main purpose of the test program was to develop corrosivity maps for the various metals tested. The test results indicated corrosion rates several times larger at coastal sites than at the inland sites. The results were presented on a map (corrosion rate, SO_2, Cl^-, temperature, and relative humidity). The authors report that statistical analysis on the test results indicated that the atmospheric parameters were not independent. It was also reported that the relative effects of the various pollutants on the corrosion rate was material dependent (i.e. the controlling parameter is not the same for different metal).

23. Cramer, S., J.P. Carter, P.J. Linstrom, and D.R. Flinn (1988). **Environmental Effects in the Atmospheric Corrosion of Zinc.** (refer to Materials)

24. Doyle, D.P. and T.E. Wright (1982). **Rapid Methods for Determining Atmospheric Corrosivity and Corrosion Resistance.** in *Atmospheric Corrosion*. W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 227-243.

The authors deal with the CLIMAT (Classification of Industrial and Marine Atmospheres) test, which is used, as the name implies, to classify atmospheric corrosivity for a given location. Experience is mainly with aluminum and its alloys but some work with other metals has also been done. The CLIMAT test is also called the wire-on-bolt test whereby the corrosion characteristics of a wire can be investigated either alone or in a galvanic couple. The authors also describe the SIMAT (Simulation of Industrial and Marine Atmospheres) test, which has been developed in order to obtain accelerated test data on various aluminum alloys, relating to atmospheric applications.

25. Dugan, C.J. and D.A. Dolske (1991). **A Twelve-Year Study of Precipitation Chemistry in Philadelphia.** *APT Bulletin, The Journal of Preservation Technology*, Vol. 23, No. 4, pp. 33-36.

A record of precipitation chemistry has been collected in a mixed residential and light industrial area in north central Philadelphia over a period extending from 1978 to 1991. The rain sampling method is described. Rain pH has been monitored closely. The results show that the rain pH has gradually decreased from the early to mid 1980's but have since increased. Results of precipitation chemistry versus wind direction are also presented. The constituents investigated were potassium ions, sulfates, nitrates, and chlorides. The potassium level was found to be associated with possibly industrial sources while sulfate and nitrate levels were relatively independent of wind direction. Chlorides were found to be associated with winds coming from the Atlantic coast.

26. Duncan J.R. and Spedding D.J. (1973). **The Effect of Relative Humidity on Adsorption of Sulphur Dioxide Onto Metal Surfaces.** *Corrosion Science*, Vol. 13, pp. 993-1001.

The authors present the results of a series of experiments on metal samples to evaluate the effect of relative humidity on the adsorption rate of SO_2. When their results were compared with the test results reported by others, it was found that sample preparation before exposure has a considerable effect on the results achieved. The authors have supplemented the results of previous studies of the effect of relative humidity on the uptake of SO_2 onto metals by using a continuous flow method to examine uptake rates on iron and zinc. It was found that there exists a "critical humidity" above which appreciable corrosion occurs. This observation was also confirmed by many other researchers. A measurable desorption of SO_2 from a zinc surface was found

after the removal from an atmosphere containing SO_2. There was an irregular desorption from an iron surface under these conditions.

27. Dutra, A.C. and R. de O. Vianna (1982). **Atmospheric Corrosion Testing in Brazil.** in *Atmospheric Corrosion*, W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 755-774.
The authors report that field testing for the evaluation of atmospheric corrosion of materials in Brazil started in 1972. The first field tests were set by Companhie Siderúrgica Nacional (CSN) in cooperation with the U.S. Steel Corporation. Since then different organizations initiated test programs in various parts of the country. The authors describe the various test programs under way and outline some of the test results. The influence of the exposure angle, chloride content in the atmosphere and distance from the sea is discussed in light of the test results presented. A total of six major test programs are described.

28. Fassina, Vasco (1988). **Environmental Pollution in Relation to Stone Decay.** (refer to Materials)

29. Flori, J.-P. (1992). **Influence des conditions climatiques sur le mouillage et le séchage d'une façade verticale** . *Cahiers du CSTB*, cahier 2606, Centre Scientifique du Bâtiment, Paris CEDEX.
The CSTB carried out an experimental study on a wall exposed to actual weather conditions in order to gain a better understanding of the fluctuations in the water content of construction materials as a function of weather conditions. The testing apparatus employed provided measurements of the weight of water in the wall element, driving rain, temperature and humidity of the air next to the wall, as well as the surface temperature of the material. A reference weather station measured the environmental climate: precipitation, sunshine, temperature, humidity, and wind. A relationship was established between the water quantities absorbed by the exterior wall and the simultaneous amounts of precipitation. The influence that solar radiation and convection conditions near the wall had on the thermal exchanges and surface masses made it possible to forecast how weather conditions affected the external wall drying behaviour.

30. Flori, J.-P. (1989). **Caractérisation des Conditions Climatiques de Mouillage et de Séchage d'une Façade Verticale.** in *Quality for Building Users Troughout (sic.) the World*, CIB 89, XIth International Congress, June 19-23, Paris, France, Theme II, Vol. 1, pp. 285-295.
This is a description of the experimental work presented in a latter paper by the same author (Flori, 1992).

31. Garden, G.K. (1978). **Design Determines Durability.** First International Conference on Durability of Building Materials and Components, ASTM STP 691, pp. 31-37.
No material is, of itself, durable or non-durable; it is the interaction of elements of environment with the material that determined its durability. Water is recognized to be a major factor affecting the performance of building assemblies. The forces that could move water inward through the openings are the kinetic energy of the rain drop, capillary suction, gravity, and an air pressure difference producing infiltration. It is shown in the paper, by means of practical examples, how these forces can be controlled through simple changes in the design of assemblies. Changing the position of materials in a wall makes it possible to the wall to fulfill its total function in such a way that only the least critical sub functions are imposed on each material. The importance of including the environment into the design (by considering changes that can be made to make the environment less severe for the critical materials) is outlined. Finally, it is emphasized that with the advent of polymeric materials, the designer is now confronted with the dilemma of chemical incompatibility. The paper is a useful paper to help identify and understand the transport mechanisms that can control the micro-environment in buildings.

32. Garrecht, H., H.K. Hilsdorf, J. Kropp (1990). **Hygroscopic Salts - Influence on the Moisture Behaviour of Structural Elements.** *Durability of Building Materials and Components*. Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 313-324.
Though high moisture concentrations in building elements occur due to capillary rise of water out of ground water, wet soil, or driving rain, sections only exposed to the free atmosphere will not exhibit high moisture concentrations over a prolonged period of time. High moisture concentrations found in elements of some masonry buildings may also be caused by a contamination of the building materials with hygroscopic salts which will absorb large amounts of water. Capillary rise per se is not the immediate cause of a high moisture content, dissolved salts are transported into the building materials by this mechanism. The authors are

attempting to develop a numerical model taking into account the boundary conditions and the salt contamination to consider the influence of salts on the moisture behaviour of structural elements.

33. Gotfredsen, H.H. (1983). **Survey of International Activities.** *Durability of Concrete Structures,* CEB-RILEM International Workshop, Copenhagen, 18-20 May, pp. 369-370.
The author presents, in table form, a summary of the research activities in Europe by CEB, RILEM, FIP, IABSE, OECD, CIB, and ISO, as well as by technical universities, public research, and private research. The technical aspects of research surveyed are: material composition, environment, structural form, and interactions between the basic parameters. It seems that the area receiving less attention at the time of the survey was the environment (macro- and micro-climatic conditions). Other aspects of concrete durability have been receiving ample attention at that time.

34. Graedel, T.E. (1988). **The Chemistry of Precipitation: Perspectives on Potential Impacts on the Corrosion of Metals.** *Degradation of Metals in the Atmosphere,* ASTM STP 965, S.W. Dean and T.S. Lee, Eds., American Society for Testing and Materials, Philadelphia, pp. 327-335.
The author looks at factors which can be used to assess the potential degradation of a metal upon atmospheric exposure, namely, the frequency of precipitation, the chemical constituents of the precipitation, and the susceptibility of the metal to those constituents. Frequency distributions of rain showers duration and rain shower depth for the Brookhaven National Laboratory in New York show that the precipitation events are of greatly differing length and intensity. Summary of dew duration from the Pendleton Experimental station shows that the occurrence of dew is strongly dependent on high relative humidity, with nearly all days on which dew formed having relative humidity greater than 90 percent lasting for 8 hours or more. Looking at the chemical constituents of precipitation, the author presents an interesting table containing 10 constituents with typical concentration in fog, dew, and rain. The change of concentration of sulfates, nitrates and hydrogen ions with time of precipitation is also presented. Data showing the change in sulfur dioxide and nitrogen dioxide concentration from 1975 to 1983 at almost 300 U.S. sites indicate that the level of SO_2 has steadily dropped while the level of NO_2 has not changed much. Very little is said about metals susceptibility to various atmospheric constituents.

35. Graedel, T.E. (1986). **Corrosion-Related Aspects of the Chemistry and Frequency of Occurence of Precipitation.** Proceedings of the Symposia on Corrosion Effects of Acid Deposition and Corrosion of Electronic Materials, F. Mansfeld et. al., editors, Proceedings Vol. 86-6, April, pp. 155-172.
The author discusses some of the corrodents which can be encountered in precipitation and be detrimental to corrosion of metals. Seven different constituents including hydrogen ion (pH), nitrates, sulfates and chlorides are discussed. The various forms of precipitation include rain, snow, dew, and fog. The results of surveys in the U.S. indicating the amount of the various constituents in the various types of precipitation are presented. The paper is interesting as it gives a good idea of the normal range of pollutants that can be expected as well as the normal ranges of precipitation quantity and duration. It is interesting to note that fog has the lowest pH of all the various forms of precipitation and the pH of fog in the LA area has been recorded to be somewhere near that of lemon and battery acid.

36. Graedel, T.E. and R. McGill (1986). **Degradation of Materials in the Atmosphere** (refer to Materials)

37. Grimm, C.T. (1985). **Corrosion of Steel in Brick Masonry.** *Masonry: Research, Application, and Problems,* Grogan and Conway, Eds., ASTM STP 871, pp. 67-87.
The author presents a discussion of the causes and protection methods for steel in masonry. Water permeance of masonry is substantially greater than that of concrete and, consequently, the thickness of cover should be greater than required for reinforced concrete. A nominal cover of 100 mm is required if black steel is used in masonry structures. Another importance of water in wall cavities is condensation of water vapour on the interior surface of the exterior brick wythe. The use of flashing to redirect the water penetrating the wall cavity back outdoors is advocated. It is recognized that water is the main factor affecting corrosion of steel in masonry. Interesting references are made to case histories where corrosion of steel in masonry corrosion prematurely and some case studies from the author are also presented. Hot dip galvanized steel or copper coated wire is recommended for ties, anchors, and joint reinforcement. Shelf angles and steel lintels should be hot dip galvanized.

38. Guttman, H. (1982). **Atmospheric and Weather Factors in Corrosion Testing.** in *Atmospheric Corrosion.* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 51-68.
The paper reviews techniques for measuring climatic/atmospheric factors that are known to have an effect on the corrosion of metals. It discusses corrosion rate studies carried out in conjunction with measurements of atmospheric factors. The need to direct future research effort to take into account conditions of actual service is stressed. Such conditions include orientation, degree of shelter, effects of corrosion product and/or foreign materials, and others. The importance of time-of-wetness of a corroding substrate is discussed in some detail.

39. Guttman, H. (1968). **Effects of Atmospheric Factors on the Corrosion of Rolled Zinc.** (refer to Materials)

40. Guttman, H. and P.J. Sereda (1968). **Measurement of Atmospheric Factors Affecting the Corrosion of Metals.** (refer to Materials)

41. Haynie, F. H. (1988). **Environmental Factors Affecting the Corrosion of Galvanized Steel.** *Degradation of Metals in the Atmosphere,* ASTM STP 965, S.W. Dean and T.S. Lee, Eds., American Society for Testing and Materials, Philadelphia, pp. 282-289.
The author first presents a brief discussion of theoretical considerations in the corrosion of metals in the atmosphere. The importance of the corrosion film in providing protection against further corrosion is emphasized. In polluted atmospheres zinc exhibits a linear corrosion rate with time indicating that the corrosion film dissolves as rapidly as it forms. Test data obtained in a test program described elsewhere for the St. Louis area were used to compare the measured effect of air pollutants with their theoretical effect. Sulfur dioxide deposition on zinc specimens was evaluated from measured concentration in the air and measured wind velocities. The corrosion rate of zinc was found to be a linear function of time. The calculation of SO_2 deposition on the surface accounted for dry and wet deposition using wind speed, dew point, relative humidity, and temperature parameters. It is recognized that the critical relative humidity at which corrosion takes place is a function of the sulfur dioxide deposition. The accumulation of particles on the surface of zinc is also recognized to influence the effective time-of-wetness. Ozone, oxides of nitrogen, sulfate and nitrates were found to have insignificant effect on the measured corrosion rates.

42. Haynie, F. H. (1982). **Economic Assessment of Pollution-Related Corrosion Damage.** in *Atmospheric Corrosion.* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 3-17.
The importance of corrosion as a product life limiting factor will increase with the necessity to conserve limited resources. Thus, an economic model to assess pollution related corrosion costs becomes a useful decision tool. Physical damage, geographic distribution, maintenance, replacement, substitution, and value lost due to decreased utility or appearances are incorporated into the model. These interrelated factors are subject to individual decisions, which can be assumed in calculating best, worst, and most likely cases for different pollution levels.

43. Haynie, F.H. (1982). **Evaluation of the Effects of Microclimate Differences on Corrosion** (refer to Materials)

44. Haynie, F.H. (1978). **Theoretical Air Pollution and Climate Effects on Materials Confirmed by Zinc Corrosion Data.** (refer to Materials)

45. Haynie, F.H. and J.B. Upham (1974). **Correlation Between Corrosion Behavior of Steel and Atmospheric Pollution Data.** (refer to Materials)

46. Hechler, J.-J. (1991). **Metal Corrosion, Wetness and Deposition at the Exterior of a Building in Montréal.** *APT Bulletin, The Journal of Preservation Technology,* Vol. 23, No. 4, pp. 20-25.
The author presents the results of an investigation of the corrosion rate of steel and copper at various locations on the exterior surface of Ecole Polytechnique in Montreal. Mini-racks were used at 44 locations on the building. Each rack was instrumented with a time-of-wetness sensor, a copper and a steel plate to measure the corrosion rate, and a nitration and a sulphation plate to measure the amount of dry deposition. The results of the investigation showed that corrosion rates can vary significantly from one point to another on the building. The trend of corrosion deterioration was different for copper and steel. It seems that the extrapolation of standard ASTM tests to real structures can be very difficult since no correlation was detected between the specimens mounted on the walls of the building and a standard rack installed on the roof of the building. The period of testing was relatively short (205 days) over fall and winter only. The author recommends that more study of this nature be conducted.

47. Hosker, R.P., E.A. Smith, J.R. White, and E.A. Heathcote (1991). **Dry Deposition to Structures: Configuration Considerations.** *APT Bulletin, The Journal of Preservation Technology*, Vol. 23, No. 4, pp. 26-32.
The authors look at the dry deposition of atmospheric pollutant on structures in terms of mass transfer. An analogy to Ohm's law is drawn whereby the potential difference is the concentration difference between the surface and the atmosphere, the current is the deposition flux, and the resistance is made up of the aerodynamic transfer resistance, the boundary layer transfer resistance, and the uptake resistance. The dry deposition of pollutants is believed to take place in three stages: the pollutants from the surrounding air mix with the air in the vicinity of the surface; the pollutants cross the surface boundary layer; they are finally captured by the surface. To study the aerodynamic and boundary layer transfers the authors have conducted wind tunnel tests using a model statue and various architectural columns. Matte black models are coated with a saturated naphthalene in acetone solution to produce a uniform white coating. In the air stream the coating sublimates and the black surface is exposed where deposition would take place. Various positions and arrangements of architectural columns were investigated. The technique is quite interesting and seems to be promising. More work is required before predictions of deposition rates can be made from wind tunnel tests. Also the technique needs to be compared with field observations.

48. Johansson, L.-G., O. Lindqvist, and R.E. Mangio (1988). **Corrosion of Calcareous Stones in Humid Air Containing SO_2 and NO_2.** (refer to Materials)

49. Justo, M.J. and M.G.S. Ferreira (1993). **The Corrosion of Zinc in Simulated SO_2 - Containing Indoor Atmospheres.** (refer to Materials)

50. Kalin, Z. (1992). **The Construction Demolition Waste Stream: Magnitude and Potential.** Proceedings, World Building Congress 1992, Montreal, Canada, Tome 1, pp. 163-165.
According to a report released in 1992 by Environment Canada, nine million metric tonnes of solid waste are created yearly only from construction and demolition. Those yearly figures for The Netherlands are reported to be 12 million imperial tons. It is estimated that, before the recession, 12 percent of Ontario's work force was employed in construction and demolition. The author discusses some of the problems encountered by municipalities in Ontario with the disposal of so much waste. Although recycling is part of the solution many problems are encountered and it remains only partially satisfactory.

51. Kucera, V. (1985). **Influence of Acid Deposition on Atmospheric Corrosion of Metals: A Review.** (refer to Materials)

52. Kucera, V., S. Haagenrud, Lyder Atteraas, and J. Gullman (1988). **Corrosion of Steel and Zinc in Scandinavia with Respect to the Classification of the Corrosivity of Atmospheres.** (refer to Materials)

53. Kudder, R.J. and K. R. Hoigard (1991). **Vapor Control and Psychrometric Monitoring in Exterior Walls.** *Water in Exterior Building Walls: Problems and Solutions*, ASTM STP 1107, T. A. Schwartz, Ed., American Society for Testing and Materials, Philadelphia, pp. 124-137.
A discussion of the measurement of temperature, relative humidity, and air pressure in exterior walls is presented. The discussion covers mostly the field work organization and instrumentation to use for such a task. The purpose of conducting the measurements discussed is to detect the occurrence of condensation inside wall. Topics such as instrumentation locations, data sampling and recording equipment, duration of the monitoring program and the interpretation of the of the data are covered. Examples are also given of recorded data to illustrate the response of the sensors to various conditions of condensation on surfaces or other phenomena related to moisture and air penetration in walls. An interesting table is provided summarizing the wall response behaviour (in terms of temperature, air response and vapour pressure) for properly designed and built walls, walls with inadequate vapour control, and walls with excessive vapour control.

54. Lambert, P. and J.G.M. Wood (1990). **Improving Durability by Environmental Control.** In *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 445-452.
The paper examines the environmental factors which influence the service life of building materials and shows how they may be controlled by the use of techniques such as coating and cladding. The paper also

examines potential risks associated with incorrect use of such techniques. For example, while sheltering concrete from the elements may be beneficial in limiting existing corrosion and slowing alkali aggregate reaction, it can also accelerate the rate of carbonation of the concrete cover leading to the destruction of the protective alkaline environment.

55. Leduc, A. (1991). **Monitoring Urban Precipitation Chemistry in the Ville de Montréal.** *APT Bulletin, The Journal of Preservation Technology,* Vol. 23, No. 4, pp. 10-12.
A description of a research program to monitor the acid precipitation in Montreal is presented. The author comments that research in Canada, so far , is based on sampling stations located outside major cities. The purpose of the program is to evaluate the chemistry of Montreal's precipitation, as one aspect of the trans-boundary pollution question. Sampling of precipitation started in March 1990. The average precipitation pH to date was 4.26 and ranges typically between pH 3.8 and 4.6. The sulfate concentration was found to be approximately double of the nitrate concentration, which is believed to be typical of North American precipitation. Storm systems from the south west were found to be more acidic with an average pH of 4.07.

56. Lipfert, F.W. (1987). **Effects of Acidic Deposition on the Atmospheric Deterioration of Materials.** (refer to Materials)

57. Lipfert, F.W., M. Benarie, and M.L. Daum (1986). **Metallic Corrosion Damage Functions for Use in Environmental Assessments.** Proceedings of the Symposia on Corrosion Effects of Acid Deposition and Corrosion of Electronic Materials, F. Mansfeld et. al., editors, Proceedings Vol. 86-6, April, pp. 108-154.
The authors present the results of a statistical analysis of atmospheric corrosion test results for zinc and galvanized steel, plain carbon steel, pure copper, and pure aluminum. The data base was assembled from published data from eight test programs covering up to 72 test sites world wide. Various statistical models were fitted to the test data and the various models were compared for the goodness of fit using the correlation coefficient and the root mean square of the residuals. Based on a comparison of the various models investigated, a best fit model was proposed and compared with previous damage functions proposed by other authors. This paper presents in a fairly detailed fashion the work of Lipfert and collaborators. It is also a good source of reference for results of field exposure tests and some of the damage functions proposed by other researchers. The list of damage functions from other researchers is very short compared to what has been published in the literature.

58. Malhotra, S.K. (1989). **Factors Which Influence Durability of Wooden Structures.** *Durability of Structures,* IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/1, pp. 193-198.
Various factors affecting the serviceability and durability of wooden structures are briefly discussed. The factors discussed in the paper are: loading (man-made and natural loads); time (duration of load and creep and fatigue of wood); temperature, moisture content and cyclic environment (wood is dimensionally stable as long as its moisture content is above the fiber saturation point); weathering, insects, fungi and other organisms, and chemicals (generally hardwoods are more susceptible to chemical degradation than are coniferous species. Alkaline solutions, which dissolve some of the hemicelluloses and attack lignin in wood, have a greater effect on wood strength than do acids. Acids make wood more brittle and reduce its strength); fire (the basic effects of fire on wood members are the reduction of cross-section and the weakening of metallic fasteners in the member).

59. Mangat, P. S. and B. T. Molloy (1992). **Factors Influencing Chloride-Induced Corrosion of Reinforcement in Concrete.** (refer to Materials)

60. Mansfeld, F. (1982). **Electrochemical Methods for Atmospheric Corrosion Studies.** in *Atmospheric Corrosion.* W. H. Ailor, Ed., John Wiley and Sons, pp. 139-160.
Past and present efforts to use electrochemical techniques for the evaluation of atmospheric corrosion phenomena are reviewed. Techniques for the determination of the time-of-wetness and the recent controversy concerning the definition of the time-of-wetness are discussed. Various approaches for measurements of atmospheric corrosion rates and the question of the efficiency of electrochemical sensors ("cell factor") are evaluated. Recent results obtained in the author's laboratory concerning the reproducibility of electrochemical measurements in a statistically designed experiment under atmospheric corrosion conditions (15 sensors of one type; RH = 65, 80, and 95%; 0.1 or 1.0 ppm SO_2) are presented.

61. Martin, K.G. and R.E. Price (1982). **Quantitative Considerations of Moisture as a Climatic Factor in Weathering.** *Durability of Building Materials*, Vol. 1, No. 2, pp. 127-140.
The authors discuss functions that relate to moisture-associated degradation of building materials. These have involved studies where some quantitative information has been given on both exposure and effect. Observations have shown that the corrosion of metals is greatly influenced by the time-of-wetness, which, in turn, can be related to the relative humidity. When UV irradiance exceeded a relatively low level, the relative humidity was found to be the most important climatic factor for chalking of paint, although no damage function could be derived. Yellowing of polyester resins was found to be influenced by the moisture content of the ambient air rather than the RH, and also independently by the temperature. Results of tests on timber showed that the temperature dependence of the loss of strength fitted an Arrhenius-type equation. Cycles of wet and dry are also influential on the deterioration of timber. This suggests that climatic factors used to characterize different sites should be in terms of mean annual air temperatures under dry and wet conditions. Climatic data for various locations in Australia are compared with similar data for Canada coastal and inland regions. Comparison of corrosion rate and time-of-wetness (expressed as RH>85%) showed that temperature was also an important factor that should be considered.

62. Masuda, Y. (1987). **Penetration Mechanism of Chloride Ion Into Concrete.** *Durability of Construction Materials*, Proceedings of the First International Conference held by RILEM, Versailles, France, Sept. 7-11, pp. 935-942.
The penetration mechanism of chloride ions into concrete structures standing in a seaside area has been analyzed by applying the diffusion theory. Other researchers have solved the diffusion equation assuming the chloride ion concentration at the surface of the concrete to be constant. This assumption is believed to be valid for structures in direct contact with sea water. In order to simulate conditions where the chloride ion are brought to the concrete surface by the atmosphere, the author considers the case where the chloride ions concentration at the surface of the concrete varies with time. Chloride ion concentrations were measured in actual buildings located at various distances from the seashore. A good correlation between the measured Cl^- concentrations and the predicted values was found to exist.

63. Matsumoto, M. and S. Fujiwara (1991). **A Study of Annual Moisture Variation in an Internally Insulated Building Wall under a Mild Climate Using a Small-Scale Model and the Similarity Laws.** *Energy and Buildings*, Vol. 16, Nos. 3-4, pp. 933-945.
The authors present an experimental method using a small-scale model of a building wall and similarity laws based on the governing equations of simultaneous heat and moisture transfer through porous media. The scale model tests are used to predict the behaviour of the real building wall using similarity laws. The technique is validated using the results of a numerical solution of the governing equations in which the values of the physical parameters are independently measured values.

64. Maurenbrecher, A.H.P. and G.T. Suter (1989). **A Loadbearing Clay Brick Masonry Deterioration Problem: Monitoring of Temperature and Moisture.** (refer to Case Studies)

65. McGee, E.S. (1991). **Influence of Microclimate on the Deterioration of Historic Marble Buildings.** (refer to Materials)

66. Mikhailovsky Y.N. and P.V. Strekalov (1982). **Atmospheric Corrosion Tests in the USSR.** (refer to Materials)

67. Moresby, J.F., F.M. Reeves, and D.J. Spedding (1982). **Atmospheric Corrosion Testing in Australasia.** (refer to Materials)

68. Nagataki, S. and H. Ohga (1992). **Combined Effect of Carbonation and Chloride on Corrosion of Reinforcement in Fly Ash Concrete.** (refer to Materials)

69. Oelsner, G. (1982). **Atmospheric Corrosion Testing in the Federal Republic of Germany.** (refer to Materials)

70. Oldfield, J.W. and B. Todd (1990). **Ambient-Temperature Stress Corrosion Cracking of Austenitic Stainless Steel in Swimming Pools.** (refer to Materials)

71. Ottar, B. (1985). **Acidification of Precipitation.** *Materials Degradation Caused by Acid Rain*, R. Baboian, Ed., ACS Symposium Series 318, pp. 2-22.

Concerns about acidification of precipitations in Europe started to appear in the late 60's. Several international projects have been completed with 26 countries participating and Canada and the U.S.A. being observers. It has been found that the acidification of precipitations in central Europe has increased over the years. The main sources of acidification are sulfuric and nitric acids. Those acids form in the atmosphere by oxidation of SO_2 and NO_x through a photochemical process. The main sources of SO_2 and NO_x are the use of fossil fuels, with 50 percent of the emissions coming from vehicular traffic. The distribution of SO_2 in North America presented by the author shows the eastern part of the North American continent as the main emission area. A map of North America with pH isopleths is presented and shows a similar distribution of acidity as that presented for the SO_2 distribution. In arid areas where pollution levels are significantly high, the SO_2 and NO_x emission stay in the atmosphere for longer periods of time. Because of the photochemical process the precipitation will be increasingly acid the longer the pollutants are allowed to stay in the atmosphere. As a consequence, precipitations with a pH of 2.5 have been reported in Iceland in the spring when the periods of sunshine are long and the amount of precipitation small. The author discusses the changes taking place in fresh water bodies and soils and the effects on vegetation and aquatic life resulting from acidification of precipitations.

72. Pfeifer, D.W., W.F. Perenchio and W.G. Hime (1992). **A Critique of the ACI 318 Chloride Limits.** *PCI Journal*, Vol. 37, No. 2, March-April, pp. 68-71.

The paper traces the changes in the requirements for chloride ions and suggests new limits based on the results of recent studies. Current ACI specifications suggest maximum chloride ion content for corrosion protection in terms of water soluble chloride. However, corrosion specialists and specifying agencies have not yet agreed on a proper method to determine water-soluble chloride. The paper suggests, based on published test results, that the current recommended maximum chloride content for reinforced concrete that will be dry or protected from moisture in service should be decreased from 1.0 % water soluble to 0.2 % acid soluble. Corrosion test data show that prestressing steel has a much greater resistance to corrosion (the time to corrosion and the chloride ion corrosion threshold are both greater) than for deformed reinforcing steel. No difference in corrosion activity is found to exist between stressed and unstressed strand. The authors suggests that the current water soluble chloride ion content for prestressed concrete is too conservative at 0.06 % by weight of cement and they suggest the use of an acid soluble chloride ion content of 0.10 % by weight of cement.

73. Roper, H. and D. Baweja (1991). **Carbonation-Chloride Interactions and Their Influence on Corrosion Rates of Steel in Concrete.** (refer to Materials)

74. Saricimen, H., A.J. Al-Tayyib, M. Maslehuddin, and M. Shamim (1991) **Concrete Deterioration in High Chloride and Sulfate Environment and Repair Strategies.** (refer to Materials)

75. Sereda, P.J. (1974). **Weather Factors Affecting Corrosion of Metals.** *Corrosion in Natural Environments*, ASTM STP 558, American Society for Testing and Materials, pp. 7-22.

The author discusses the implication of the definition of the time-of-wetness and its importance on the prediction of the corrosion of metals in the atmosphere. Although there is still doubt regarding the level of humidity that should be taken in determining percentage time-of-wetness and whether it is different for each metal, it is clear that the corrosion process is definitely related to it and that prediction of relative corrosivity at a given site can be improved if time-of-wetness can be predicted. The author presents, in the form of a literature review the effect of time-of-wetness, level of sulfur dioxide, chlorides, corrosion products and temperature on atmospheric corrosion.

76. Sereda, P.J., S.G. Croll and H.F. Slade (1982). **Measurement of the Time-of-Wetness by Moisture Sensors and Their Calibration.** In *Atmospheric Corrosion of Metals*, ASTM STP 767, S.W. Dean, Jr., and E.C. Rhea, Eds., American Society for Testing and Materials, pp. 267-285.

A 1-year program involving several laboratories located in different climatic zones has afforded an opportunity to evaluate the response of miniature moisture sensors to surface moisture on panels exposed to the atmosphere. The authors present the results of a round-robin evaluation of the moisture sensor developed at NRCC. It was shown that when these moisture sensors are placed on the surface of metal or plastic panels they respond to moisture conditions at the sensor surface and that such moisture conditions result from interaction of the total environment with the material as well as with the ambient relative humidity conditions.

77. Skerry, B.S., J.B. Johnson, and G.C. Wood (1988). **Corrosion in Smoke, Hydrocarbon and SO_2 Polluted Atmospheres - I. General Behaviour of Iron.** (refer to Materials)

78. Skerry, B. S. , J.B. Johnson, and G.C. Wood (1988). **Corrosion in Smoke, Hydrocarbon and SO_2 Polluted Atmospheres - III. The General Behaviour of Zinc.** (refer to Materials)

79. Southwell, C.R. and J.D. Bultman (1982). **Atmospheric Corrosion Testing in the Tropics.** (refer to Materials)

80. Tomiita, T. (1992). **Solar UV, Wetness and Thermal Degradation Maps of Japan.** *Construction & Building Materials*, Vol. 6, No. 4, pp. 195-200.

The author presents contour maps of deterioration factors obtained from meteorological data collected at approximately 150 locations in Japan. The yearly amount of solar UV energy (measured for part of experimentation with a photodiode) was calculated from the solar altitude and the hourly range of solar energy measured with a pyranometer. The values obtained can serve as a guide for the severity of the climatic conditions on polymeric building materials. The wetness time was estimated as the time during which the relative humidity was greater than 80 percent while the temperature was above freezing (it may also have been determined from dew point calculations: the paper is not clear in this respect). The number of wet-dry cycles per year was also obtained. The black panel temperature, which is an index of the severest thermal degradation conditions, was measured at 66 locations in Japan and the results were used to calculate a daily equivalent black panel temperature. The maximum daily temperature range was calculated using minimum and maximum measured temperatures corrected for the effect of wind and cloud cover.

81. Weaver, M.E. (1991). **Acid Rain and Air Pollution vs. the Buildings and Outdoor Sculptures of Montréal.** *APT Bulletin, The Journal of Preservation Technology,* Vol. 23, No. 4, pp. 13-19.

A brief description of the deterioration process of various materials (metals, stones and masonry, glass) exposed to acid rain is given. Various deterioration problems are outlined and concrete examples of such occurrences in Montreal are given. It is stressed that deterioration caused by acidic precipitation and air pollution is the result of extremely complex interactions involving chemical, physical and physico-chemical processes. The time-of-wetness is said to be the most important factor in the atmospheric corrosion of metals. It is also an important factor with other materials. Rough or highly textured surfaces have relatively large surface areas in comparison with smooth or polished surfaces, are wetted more easily and remain wet longer. Examples of pollution induced deterioration in Montreal are given for stone, metals, and stained glass. Remedial and protective measures against the effects of pollution are proposed. Finally, the author states that the assessment of risks of pollutant-accelerated deterioration need to be factored into cost-benefit ratios. The initial investment in stainless steel flashings and roofs is offset by avoiding the risk of interior damage from leaks and the cost of maintenance.

82. Williams, M.F. and B.L. Williams (1991). **Water Intrusion in Barrier and Cavity /Rain Screen Walls.** *Water in Exterior Building Walls: Problems and Solutions*, ASTM STP 1107, T.A. Schwartz, Ed., American Society for Testing and Materials, pp. 1-10.

The authors discuss two exterior wall concepts - barrier and cavity/rain screen - as they relate to water penetration. Typically, a barrier wall is designed to prevent water intrusion. On the other hand the cavity and rain screen walls allow water penetration into the wall assembly (to the air cavity) but are designed to manage the water infiltration by redirecting it to the outside. The rain screen relies on pressure equalization between the outdoor and the air cavity to minimize water infiltration. Therefore, the cavity in a rain screen is usually smaller than that in a cavity wall in order to allow for fast equalization. The authors discuss various deficiencies of two wall systems encountered when workmanship is not adequate.

83. Yamasaki, R.S., H.F. Slade, and P.J. Sereda (1983). **Determination of Time-of-Wetness Due to Condensed Moisture.** *Durability of Building Materials,* Vol. 1, No. 4, pp. 353-361.

The authors present the results of an experimental evaluation of the time-of-wetness on a metal surface caused by condensation of moisture as opposed to wetting from precipitation. Time-of-wetness resulting from condensation of moisture on an exposed metal surface is believed to be more detrimental than that resulting from precipitation. This is due to the fact that SO_2 will be present in higher concentration in moisture than in rain. Furthermore, rain washes the surface and makes the environment cleaner than for moisture condensation. In order to separate the two sources of wetting of the surface of a metal, the authors used two stainless steel plates, one slightly heated and the other at ambient temperature of the exposure site. The heated plate was used to measure the time-of-wetness due to rain precipitation while the other plate measured the time-of-wetness resulting from both precipitation and moisture condensation. Measurements over a period of one year showed that the time-of-wetness resulting from moisture condensation alone is about twice as long as the time-of-wetness resulting from precipitation alone. The time-of-wetness was measured using a surface moisture sensor developed by the third author.

84. Zak, T. and G. Chojnacka-Kalinowska (1982). **Evaluation of Corrosivity of Various Atmospheres.** in *Atmospheric Corrosion,* W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 217-226.

The atmospheric corrosion of low-carbon steel in various climatic conditions (at 14 weather stations located in different regions of Poland) was examined. Corrosion losses were determined at monthly intervals for two years. The results obtained were correlated with meteorological parameters and SO_2 concentrations. Suitability of one and multi-parameter equations was statistically determined. The best results were obtained when correlating the corrosion rate (K) and the time when the specimen is wet. The wet time was calculated from the difference of air and dew point temperatures. The rate of corrosion was found to be best predicted using the equation $K = at_B + b$ where a and b are the regression coefficients and t_B is the time-of-wetness. This equation was found most suitable for predicting the corrosion losses in Poland.

Components and Assemblies

1. ACI Committee 546, (1980). **Guide for Repair of Concrete Bridge Superstructures.** *Concrete International*, Vol. 2, No. 9, Report No. ACI 546.1R-80, pp. 69-88.

ACI Committee 546 presents guidelines for repair of concrete bridge superstructures (pier caps, beams, decks, curbs, sidewalks, and rails). More specifically, guides are provided for the evaluation of damage and selection of repair method, methods of surface preparation, a description of portland cement concrete, latex modified portland cement and polymer concrete. A list of references containing 46 references is also presented.

2. Akoz, F. and M.S. Akman (1990). **Service Life Estimation for Multi-Ply Flat Roof Membranes.** *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 353-358.

A method of predicting the service life of bituminous multi-ply roofing elements is presented. The damage factors investigated were wetting-drying, wetting-partial drying, freezing-thawing, surface heating-cooling and ultraviolet radiation. Tests were conducted both in laboratory and in the field. The tensile strength of samples was measured at various numbers of cycles to assess the level of deterioration. After expressing the serviceability by a measurable property (tensile strength) it was possible to predict the life based on the regional characteristics of the damage factors. A correction factor was applied to the accelerated test results to account for the discrepancy between the lab observations and the field observations.

3. Allan, J.A. (1992). **Retrofit Ties for Brick Veneer.** (refer to Materials)

4. Anon. (1993). **Removing Chloride Ions from Reinforced Concrete.** (refer to Environment)

5. Anon. (1983). **External Masonry Walls Insulated With Mineral Fibre Cavity-Width Batts: Resisting Rain Penetration.** Building Research Establishment Housing Defects Prevention Unit, Defect Action Sheet DAS 12, February.

This bulletin describes the action to take to prevent water penetration to the inner leaf of an exterior wall when the wall cavity is completely filled with mineral fibre insulation batts and mortar is extruding in the horizontal joints between batts. Although the batts are treated to make them water repellent, when there is mortar in the horizontal joint between the batts, rainwater can penetrate to the inner leaf. The mortar can either be mortar droppings or extrusions from bed joints.

6. Anon. (1980). **Water Leaks Plague Museum.** (refer to Case Studies)

7. Anon. (1980). **Facades: Errors can be Expensive.** (refer to Case Studies)

8. Anon. (1979). **GAO Decries Bridge Deck Corrosion.** (refer to Case Studies)

9. Anon. (1973). **LBJ Library Needs $1.8 Million Repair.** (refer to Case Studies)

10. Arbogast, D. (1990). **Problems Affecting the Service Life of Exterior Sandstone: Case Study, the Burlington, Iowa Free Library.** (refer to Case Studies)

11. Arup, H. (1983). **Prospects Concerning Corrosion of Steel in Concrete.** *Durability of Concrete Structures*, CEB-RILEM International Workshop, 18-20 May, Copenhagen S. Rostam, Ed., pp. 345-350.

The author discusses the use of half cell potential measurement for assessing the state of corrosion of steel embedded in concrete. The importance of half cell potential measurements as a non-destructive testing/inspection technique is emphasized. The electrochemical potential mapping as described in the ANSI/ASTM C 876-77 has been used especially for highway bridge decks and should be used with caution in other types of structure. A laboratory investigation of bridge deck corrosion is presented. The parameters which were under examination were epoxy coating of one or both rebar layers and the application of a low permeability coating on slabs where corrosion had already been initiated. It was found that the coating of the underside of the slab reduced the current much more than a coating of the top layer (the coating of the underside reduces the amount of oxygen available to the bottom steel for the cathodic reaction). It was found that most of the corrosion of the top layer was contributed by the contact with the bottom layer. If the bottom layer is prevented from reacting with the oxygen e.g. by epoxy coating, this contribution can be prevented.

12. Attwood, D., M.A. Nessim, A. Ghoneim, A. Cormeau, and M.S. Cheung (1991). **Application of Reliability Theory to in-Service Monitoring and Maintenance of Parking Garages.** *Canadian Journal of Civil Engineering*, Vol. 18, pp. 781-788.

    The paper presents an example of the application of reliability theory to in-service monitoring and maintenance. The time-dependent deterioration of a reinforced concrete indoor parking structure's driving surface is considered. Based on an estimated rate of slab delamination, crack width in the concrete cover, and the effect of temperature on the rate of corrosion, the authors have derived a model which relates the amount of delamination to the age of the garage, crack width, temperature, and time to deterioration (which in turn is dependent on the depth of the cover, water-cement ratio, and chloride ion concentration). The concepts used in the assessment of parking garage reliability described in this work may be applied to a variety of structures and building systems in order to make decisions regarding different aspects of in-service maintenance and repair.

13. Babaei, K. and N.M. Hawkins (1988). **Evaluation of Bridge Deck Protective Strategies.** *Concrete International,* Vol. 10, No. 12, pp. 56-66.

    The authors present the existing knowledge of different common strategies for protecting bridge decks against deterioration caused by de-icing salts. The strategies considered are: increased cover to the top bars; low-slump, dense concrete overlay; latex-modified concrete overlay; interlayer membrane/asphalt concrete system; and epoxy coated bars. The authors propose practical guidelines to make each strategy acceptable from a point of view of durability. To achieve a 50-year or more effective service period, designs must consider the severity of salt application, the water/cement ratio and the cover thickness. A cost effectiveness study of the protection strategies (either single or double protection) was performed. For single protection, provision of a concrete cover of 3.5 in. is the least expensive. For double protection decks, provision of top and bottom mats' epoxy coated rebars was found to be the least expensive.

14. Baker, M.C. (1969). **Designing Wood Roofs to Prevent Decay.** Canadian Building Digest, Division of Building Research, National Research Council of Canada, CBD 112.

    In an earlier digest by the same author (CBD 111) excessive moisture content of wood (above 35 percent or so) was identified as the major cause of wood decay which can be most easily controlled. In order to prevent wood decay the moisture content of wood must be maintained below 20 percent. The author deals with some of the moisture conditions to be considered in the design of wood roofs. In normal building environments the moisture content of wood varies between 5 percent in the winter and 15 percent in the summer. Higher moisture contents which can lead to rotting of wood can however be reached when building systems are improperly designed or built. Venting on the cold side of insulation would provide a means of disposing of the moisture which will reach the cold side of the deck. Under normal conditions it is believed that condensation of moisture is not a problem when properly dried wood is used for the construction. The wood absorbs the moisture and releases it again when the temperature rises. The use of vapour barriers can be a problem in cases where the deck is enclosed between the vapour barrier and the roofing membrane. In such a case the moisture in the deck will get trapped and may cause decay, especially if the deck was exposed to rain before the roofing and the vapour barrier were installed.

15. Baronio, G., M. Berra, L. Binda, and A. Fontana (1989). **Durability of Masonry Strengthening by Injection Techniques.** in *Durability of Structures*, IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/2, pp. 755-760.

    Brick masonry prisms, prepared with different types of mortar, were subjected to compression tests up to failure. The cracked prisms were injected with epoxy resin or cement-polymer grout and retested. Injection of the failed prisms restored an average of 85% of the original strength. The stress-strain curve of the injected specimens tend to remain similar to those of the prisms under the first compression test. A correlation was found to exist between the ultrasonic pulse velocity and the strength of the prisms both in the virgin and injected conditions. It seems that the authors have a different concept of durability than everybody else. The problem of durability (i.e. how the repaired structure will stand with time) is not addressed

16. Barrett, P. (1983). **Rain Penetration Through Masonry Walls.** *Insulation Journal,* Vol. 27, No. 11, November, pp. 35-36, 38-39.

    A significant change in the construction industry which took place over the years is believed to be partly responsible for water penetration problems in buildings. The change from local builders to the national builder and the bricklayer becoming a subcontractor is responsible for the loss of knowledge of local climatic conditions and the loss of skills of recognition and remedial techniques. The change in composition of the mortar (lime being replaced by plasticisers) has resulted in much more permeable mortar being used nowadays than was used previously. The author discusses problems of water penetration through masonry cavity walls. A brief discussion of the development of exposure zones developed in terms of driving rain and used in BS 5618 (Code of Practice for Thermal Insulation of Cavity Walls) indicates that the present exposure system provides a realistic guide to suitable building construction when used in conjunction with UF foam cavity wall insulation. The influence of cavity insulation on wall resistance to rain penetration is also discussed.

17. Beall, C. (1990). **Building Joint Movement.** In *Serviceability and Durability of Construction Materials*. Proceedings of the First Materials Engineering Congress, Denver, CO., Aug-13-15, Vol. 1, pp. 517-526.

The factors affecting joint movement in masonry cladding and sealant failure are discussed as parameters for sizing and detailing brick expansion and concrete masonry control joints. Control joints in masonry should provide room for contraction and expansion due to temperature changes and moisture variation. In order to minimize the strain on the joint sealant, the sealant should be placed at mean temperature. In order to minimize the stress on the joint sealant the joint depth should be less than or equal to the joint width.

18. Beasley, K.J. (1990). **Leaking Brick-Clad Walls: Causes, Prevention, and Repair.** ASCE *Journal of Performance of Constructed Facilities*, Vol. 4, No. 2, May, pp. 124-133.

The author discusses some common problems which cause leaks in brick-clad walls. Those are: improper flashing, improper drainage of the cavity, presence of mortar droppings in the cavity which bridge the cavity and allow access of water to the backup wall, deteriorated of improper mortar joints, deterioration of sealants in expansion joints. The author does not discuss any specific field experience but rather presents a guide to proper design and workmanship. Recommendations for repair are given. The paper does not present any new material that has not already been discussed in many other papers.

19. Beasley, K.J. (1988). **Use and Misuse of Exterior Travertine Cladding.** (refer to Materials)

20. Binda, L. and G. Baronio (1989). **Performance of Masonry Prisms Repaired by Grouting under Various Environmental Conditions.** *Masonry International*, Journal of the British Masonry Society, Vol. 3, No. 2, pp. 74-79.

The authors have investigated a repair technique by injection of epoxy resins or cement-polymer grouts into masonry prisms. The description of the test program and the findings have been described in Baronio et. al. (1989) and have been summarized above. No new information is presented in this paper. Salt decay was not stopped by the technique. Temperature variations influenced the behaviour of masonry repaired by resins: freezing increases the material stiffness and brittleness, thawing, on the contrary, decreases both stiffness and strength.

21. Binda Maier, L., P.P. Rossi, and G. S. Landriani (1983). **Diagnostic Analysis of Masonry Buildings.** *Strengthening of Building Structures - Diagnosis and Therapy.* IABSE Symposium, Venezia, IABSE reports Vol. 46, pp. 131-138.

The authors describe operative criteria for the stress analysis of masonry buildings for which data on local geometrical configuration, physical properties of materials and loading history are incomplete. The authors discuss the use of in-situ non-destructive tests to obtain stress and strain states in masonry buildings. In-situ tests based on the insertion of special flat jacks in the masonry represent a useful tool to determine the mechanical behaviour of the material without extracting samples.

22. Bjegovic, D., V. Ukraincik, and Z. Beus (1990). **Evaluation and Repair of Concrete Structure in Urban Environment: Case Study.** (refer to Case Studies)

23. Brandt, E. (1984). **Assessment of the Conditions of Buildings.** Third International Conference on the Durability of Building Materials and Components, Espoo, Finland, August 12-15, Vol. 2, pp. 433-439.

The paper discusses in very general terms different types of maintenance and inspection. It also gives suggestions on how to treat the information collected during inspections in order to make inspection routines and evaluation of rest of life simple. Guidelines about reporting inspection observations are given. It is suggested that rest of life time predictions should be made subjectively by experienced engineers.

24. Bright, K. D. (1991). **Testing Cathodic Protection Systems.** *Concrete International,* Vol. 13, No. 7, pp. 37-39.

The author reports the results of a two year study of various cathodic protection systems for rehabilitating a parking garage. The parking structure showed signs of deterioration ten years after its construction. Three years after the repairs the slab was again showing distress. A total of 11 different cathodic protection systems were implemented on a section of the slab to assess the performance of the systems. In general, the performance of the systems was disappointing. It appears that any top system that inhibited moisture from wetting the surface had poor performance. The most effective system was estimated to cost 3.75 $\$/ft^2$. The

author expressed the opinion that anyone considering a cathodic protection system should first test it on the actual structure to measure its potential performance.

25. British Standard (1992). **Guide to Durability of Buildings, and Building Elements, Products and Components.** BS 7543 : 1992.
The Standard gives guidance on durability, required and predicted service life and design life of buildings and their components and/or parts. It applies primarily to new buildings rather than to alterations and repairs. Guidance is also given for presenting information on the service and design life of buildings and parts.

26. Browne, R.D. (1982). **Design Prediction of the Life for Reinforced Concrete in Marine and Other Chloride Environments.** *Durability of Building Materials,* Vol. 1, No. 2, pp. 113-125.
Corrosion generally occurs when the electrical resistivity of the concrete cover to steel is low, when atmospheric oxygen can diffuse through the cover layer, and when the chloride level of the steel surface is 0.4% by weight of cement. Where any one of the three factors is absent, damage does not occur. A relationship between the rate of chloride diffusion and the chloride diffusion coefficient is proposed from which the time required for the Cl^- concentration at the steel reaches a critical value can be predicted. The time of onset of corrosion is predicted from the diffusion rate of the chlorides from the environment through the concrete cover. This time scale is used as a basis for predicting the service life of the structure. The additional time required to cause spalling of the concrete cover is believed to be from 6 months to 5 years depending on the availability of oxygen and the quality of the concrete. For corners it is believed that the life may be approximately halved because of the two-directional diffusion path from the two sides. Evidence is emerging that the use of cement replacement materials (pulverized fuel ash and blast furnace slag) can reduce the chloride diffusion coefficient by significantly reducing the size of the interconnected pores in the hardened cement. Various field measurements are proposed which can assess the condition of the concrete structure before spalling starts. Simple repairs are also proposed to extend the service life depending on the state of deterioration of the concrete structure. (This seems to be a promising technique of assessing the existing condition of concrete bridge decks and predicting their remaining service life before damages become visible. However, the threshold chloride concentration is not as well established as the author believes. The problem of carbonation of concrete was not addressed).

27. Building Research Association of New Zealand (1984). **Sealed Joints in External Claddings - 2. Sealants.** Building Information Bulletin 239.
This bulletin gives a description of various types of sealants used in the construction industry for sealing glazing and cladding. The various sealants are classified by chemical type and by movement type. A table is provided in which 12 different types of sealants have been described in terms of the substrate suitability, the maximum recommended movement, the expected service life and their typical uses. The durability of the listed sealants range from 5 years for bituminous sealants to 20 years for silicone an polysulfide sealants. Guidelines are given for the proper joint preparation, sealant application and maintenance.

28. Building Research Establishment (1992). **Flat Roof Design: Waterproof Membranes.** BRE Digest 372, June.
Various roofing systems are reviewed. A description of built-up roofing with its various components is given. This system consists of two or three plies of bituminous felt. Polymeric single-ply membranes are also described. The types of polymers, the methods of forming the joints and the methods of attachment are discussed. Liquid-applied membranes are used for remedial work or to prolong the life of existing membranes. Mastic asphalt consists of two 10 mm layers of asphalt mix. The mastic asphalts are vulnerable to movements since the mastic is relatively hard and brittle once it sets. Durability of roofing membranes is briefly discussed. The durability of membranes seems to be closely related to their fatigue resistance. Fatigue test results on various membrane systems are presented.

29. Building Research Establishment (1991). **Why do Buildings Crack?** BRE Digest 361, May.
The digest examines the causes of cracking in buildings and shows the visible results of a wide range of problems. The causes of cracking outlined are: differential movements of various parts of a building, temperature changes, drying of moisture and wetting and drying, freezing and thawing, sub-surface crystallization of soluble salts, sulfate attack, corrosion of embedded steel, moisture expansion of fired clay products, alkali silica reaction, imposed load effects, foundation movement, and vibration.

30. Building Research Establishment (1977). **Repairing Brickwork.** BRE Digest 200, April.
This digest is concerned with damage to small buildings. Various causes of damage are referred to briefly. The causes of damage reviewed are: ground movement resulting from movement of the water table, frost heave, vibration; thermal movement ; drying shrinkage; fire; roof spread where pitched roofs have been inadequately tied; sulfate attack; expansion on wetting; corrosion of embedded steel; unsound materials;

frost when the brick is very wet; salt which produces efflorescence. Guidelines are given to repair damage. For brick veneer showing signs of tie corrosion, it is recommended that the old ties be removed and new corrosion resistant (stainless steel, carefully protected steel, non-ferrous metal) ties be placed.

31. Building Research Station (1966). **Cracking in Buildings.** Digest 75, Second Series, October.
This digest examines the causes of cracking in buildings and shows, with the help of illustrative examples, how an understanding of the factors responsible is necessary for correct diagnosis and repair. The main cause of cracking of masonry walls is the lack of provision in the design for expansion of the bricks that takes place when brickwork is exposed to moisture. Frost heave, differential settlement, sulfate attack, thermal movements, and deflection of floors are also identified as causes of cracking.

32. Cady, P.D. and R.E. Weyers (1983). **Deterioration Rates of Concrete Bridge Decks.** *Journal of Transportation Engineering*, Vol. 110, No. 1, pp. 34-44.
Procedures are presented for estimating the parameters required for life-cycle costing of the elements of maintenance and rehabilitation of concrete bridge decks subject to the deteriorative effects of deicing chemicals. As background information, the authors discuss the nature of the deterioration process taking place in deck slabs. They also discuss expressions used to evaluate the time of cracking as derived by Bazant and time to initiation of cracking. The authors present a method to estimate the time at which rehabilitation of the deck is likely to be necessary and the time at which beginning of maintenance is necessary. The methodology is neither applicable to bridges containing epoxy coated reinforcement, nor to overlaid or cathodically protected decks for which chloride penetration rate and corrosion rate are not known.

33. Carlson, A.R. (1991). **Computer Simulation of Wall Condensation Problems.** (refer to Environment)

34. Carrier, R.E. and P.D. Cady (1973). **Deterioration of 249 Bridge Decks.** (refer to Case Studies)

35. Cassady, L.W. (1990). **Incompatibility of Building Components.** ASCE *Journal of Performance of Constructed Facilities,* Vol. 4, No. 1, February, pp. 21-23.
The author reports about a storage facility consisting of a steel frame with precast panel walls and a roof with a ballasted single-ply membrane with galvanized metal edge flashing and gutters. After only three years of construction the gutters had been perforated by corrosion. The expected service life of the gutters was 20 years. The problem was found to be the roof ballast which contained significant amount of iron, aluminum, magnesium, and silicon. The minerals were being washed away by rain and deposited in the gutters where it would set an electrolytic cell with the gutters causing accelerated corrosion of the zinc coating on the gutters.

36. Chrest, A.P. (1990). **Structural System Performance in Parking Structures.** *Concrete International,* Vol. 12, No. 8, pp. 30-34.
The author considers cast-in-place conventionally reinforced concrete structural systems, and thin slab cast-in-place conventionally reinforced concrete structural systems, to be less suitable than other structural systems for parking structures. The author recommends cast-in-place post-tensioned concrete one way slab and beam or precast pretensioned pretopped concrete double tee systems. Structural systems that require surface coatings or other relatively expensive protective measures to make them durable in corrosive environments should be avoided.

37. Cohen, J.M. (1991). **Cladding Design: Whose Responsibility?** *Journal of Performance of Constructed Facilities*, ASCE, Vol. 5, No.3, pp. 208-218.
The author looks at some of the issues involved in the design of building cladding. Some of those issues consist of durability and integrity of cladding materials, analysis and structural design, education, practice, and future uses of cladding. The author reports that, in a 1990 survey conducted by the ASCE's Research Committee of the Technical Council on Forensic Engineering, durability of man-made building materials was noted as one of the most important research topics. The paper discusses mostly aspects related to the use of natural stones for cladding. It is noted that there is a lack of communication and collaboration between the architects and structural engineers and there is a greater lack in teaching on the building envelope. Cladding are required to carry wind loads and their anchors must resist the same loads and the weight of the cladding and, as such, their design requires the expertise of structural engineers. Finally the author observes that there is growing trend towards structural engineers looking at cladding as a structural element. Research work quoted by the author indicated that cladding not only carries the environmental loads to the framework, but also contributes significantly to the stiffness of buildings and plays an important role in frame members force distribution.

38. Cohen, J.M. and P.J.M. Monteiro (1991). **Durability and Integrity of Marble Cladding: A State-of-the-Art Review.** (refer to Materials)

39. Comité Euro-International du Béton (1989). **Durable Concrete Structures - CEB Design Guide.** (refer to Environment)

40. Comité Euro-International du Béton (1990). **CEB - FIP Model Code 1990.** First Draft Chapters 1-5, CEB Bulletin d'Information No. 195, March.

Section 1.5 of the Model Code presents a discussion of the principles of design versus durability. It is believed that if a structure is designed, executed and maintained according to the requirements of the Model Code, there is a high probability that it will withstand the expected conditions of use for a long period of time (50 years or more).

41. Comité Euro-International du Béton (1990). **CEB - FIP Model Code 1990.** First Draft Chapters 6-14, CEB Bulletin d'Information No. 196, March.

Chapter 8 of the Model Code covers aspects of durability. Design strategies to adopt in order to obtain a structure with adequate durability are outlined. Design criteria for durability take the form of recommendations with respect to: the structural form; composition of the concrete material and the cover thickness for reinforcing steel and prestressing steel; detailing; nominal crack width limitation; and, special protection such as use of structural protection such as roof projection, use of surface coating, increase of concrete cover, modification of the micro-environment, coating of reinforcement, cathodic protection, etc.

42. Cuoco, D.A. and E.E. Velivasakis (1989). **Aluminum Curtain Wall Panel Failure, Assessment and Repair.** (refer to Case Studies)

43. Davies, H. (1990). **Studies of the Performance of Fusion Bonded Epoxy Coated Reinforcement During the Construction Process.** (refer to Materials)

44. de Vekey, R.C. (1989). **The Durability of Steel in Masonry.** *British Ceramic Transactions and Journal*, Vol. 88, No. 5, Sept. - Oct., pp. 201-203.

Problems and failures of steel in brickwork exposed to outdoor conditions are quite common. The paper reviews the mechanism of failure, and the way to specify to avoid failure in relation to some of the key factors such as the exposure condition, type of steel alloy and protective coating system if used. Factors such as the chemical nature of the environment, the effectiveness of any protective systems and type of steel alloy are briefly discussed. Carbonation of mortar is noted as the principal cause for corrosion of steel embedded in mortar, along with ingress of chlorides. Zinc and epoxy coatings are the two most widely used protective coatings for steel in masonry. The paper also presents a list of 27 references related to the durability of metals in masonry.

45. Dreger, G. T. (1989). **Cementitious-Cladding Failure - A Building Façade Collapse: An Odyssey of Failure and Lessons Learned.** (refer to Case Studies)

46. El-Sayed, H.A., M.G. Abd El-Wahed and A.H. Ali (1987). **Some Aspects of the Corrosion of Reinforcing Steel in Concrete in Marine Atmospheres.** (refer to Case Studies)

47. Fookes, P.G., C.D. Comberbach and J. Cann (1983). **Field Investigation of Concrete Structures in South-West England, Part I** (refer to Case Studies)

48. Fookes, P.G., C.D. Comberbach and J. Cann (1983). **Field Investigation of Concrete Structures in South-West England, Part II** (refer to Case Studies)

49. Freyermuth, C.L. (1991). **Durability of Post-Tensioned Prestressed Concrete Structures.** *Concrete International*, Vol. 13, No. 10, pp. 58-65.

The author presents a brief summary of the research in the area of durability of post-tensioned prestressed concrete, experience on the durability of post-tensioned bridges (bridge decks, segmental concrete bridges, stay cables) and buildings. The various research projects showed that post-tensioning can provide substantial improvement of durability by eliminating cracks and limiting crack width. The various case studies reported by the author indicate that the cause of deterioration and low durability of existing post-tensioned structures can be traced to deficient design and substandard workmanship. "Recent improvements in corrosion protection materials for tendons and stay cables provide a very high degree of assurance of long-term durability in future bridges".

50. Freyermuth, C.L., P. Klieger, and D.C. Stark (1970). **Durability of Concrete Bridge Decks - A Review of Cooperative Studies.** (refer to Case Studies)

51. Green, P. (1988). **Structures Need a Low-Sodium Diet.** (refer to Case Studies)

52. Green, P. (1986). **Owners Reclad Damaged Masonry.** (refer to Case Studies)

53. Grimm, C.T. (1985). **Corrosion of Steel in Brick Masonry.** (refer to Environment)

54. Grimm, C. T. (1976). **Metal Ties and Anchors for Brick Walls.** *Journal of the Structural Division*, Proceedings of the ASCE, Vol. 102, No. ST4, April, pp. 839-858.
The paper presents an extensive description of metal ties and anchors used for brick walls. The various types of ties and anchors, the materials used for their manufacture, and the tested capacity of the various types of connectors are discussed. The estimated allowable axial load on typical wall anchors varied from 80 lb to 920 lb.

55. Gulikers, J. (1989). **Influence of Local Repairs on Corrosion of Steel Reinforcement.** *Durability of Structures*, IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/1, pp. 151-156.
A description is given of a concrete corrosion cell which has been developed to investigate the effect on the corrosion process of the mutual influence between rebars in carbonated concrete and rebars embedded in repair mortar. It was found that rebars embedded in mineral mortars can develop into macro cathodes, the rate of their reactivity being mainly determined by the diffusion of oxygen. When these macro cathodes are electrically connected with rebars in carbonated concrete an acceleration of their anodic processes will occur. For rebars partly embedded in repair mortar and partly in carbonated concrete it is likely that the small macro anode will occur next to the large macro cathode.

56. Haver, C.A. (1989). **Corrosion of Steel Embedded in Masonry Walls.** (refer to Materials)

57. Haver, C.A., D.L. Keeling, S.Somayali, D. Jones, and R.H. Heidersbach (1990). **Corrosion of Reinforcing Steel and Wall Ties in Masonry Systems.** (refer to Case Studies)

58. Heidersbach, R. and J. Lloyd (1985). **Corrosion of Metals in Concrete and Masonry Buildings.** (refer to Case Studies)

59. Heidersbach, R., B. Borgard, and S. Somayaji (1987). **Corrosion of Metal Components in Masonry Buildings.** (refer to Case Studies)

60. Karni, J. (1982). **The Durability of Prefabricated Reinforced Concrete External Walls and Cladding in Buildings.** *Durability of Building Materials*, Vol. 1, No. 2, pp. 141-160.
An investigation was initiated to assess the durability of prefabricated reinforced concrete external wall panels used in several industrialized building systems throughout Britain. To compare the degree of exposure, the Index of Exposure to Driving Rain was used. The survey was planned to include visits to prefabricated-element factories and to building sites, as well as tests at B.R.S. laboratories on materials obtained from the factories. An analysis of the preliminary observations showed that location of the most common weakness of the exposed buildings was at the panel-to-panel joints rather than in the panels themselves. The quality of the panels included in the survey was found to be good and deterioration after 8 years of observation was found to be non-existent. However, more observation, over many more years, are required to assess the panels' durability.

61. Keller, H., T.W.J. Trestain and A.H.P. Maurenbrecher (1992). **The Durability of Steel Components in Brick Veneer/Steel Stud Wall Systems.** (refer to Case Studies)

62. Lin, C.Y. (1980). **Bond Deterioration Due to Corrosion of Reinforcing Steel.** *Performance of Concrete in Marine Environment*, ACI Publication SP-65, pp. 255-269.
The author presents the results of an experimental investigation conducted to determine the effect of flexural cracks on the rate of corrosion of reinforcement and the reduction in bond strength due to longitudinal corrosion cracks. The tests were performed on concrete beams exposed to sea water under impressed currents. The tests showed that, for a given flexural crack size, the higher the impressed current, the faster the longitudinal crack will start. Under constant impressed current, the corrosion rate is not affected by the flexural crack width. If cracking results from the application of an overload and the crack is allowed to close,

the corrosion rate is significantly reduced compared to the condition where the crack remains open. For beams with continuous reinforcement, the moment capacity was reduced from 12 to 50 percent under impressed currents of 5 to 10 mA/cm^2. About 35 percent of the bond stress was found to be lost from corrosion in beams designed with lapped splices. The resistivity of the concrete was found to play an important role in the susceptibility to corrosion of the reinforcement.

63. Litvan, G.G. (1990). **Performance of Parking Garage Decks Constructed with Epoxy Coated Reinforcing Steel.** (refer to Case Studies)

64. Litvan, G.G. (1982). **Evaluation and Repair of Deteriorated Garage Floors.** Canadian Building Digest, Division of Building Research, National Research Council Canada, CBD 225.

This digest describes the methods used for the assessment of damages and how these tests can aid in the selection of the repair method. Visual inspection is performed to detect possible structural defects, cracks in the deck, the conditions of beams and columns and to identify as accurately as possible the cause of deterioration. The drainage conditions and condition of expansion joints is also assessed during the visual inspection. A delamination survey using a chain dragged over the surface of the deck identifies location where corrosion has progressed to a point where the concrete cover has failed. A cover meter survey using a pachometer identifies the thickness of the concrete cover. Measurement of corrosion potential can identify locations where corrosion is taking place but cannot assess the corrosion rate. Measurement of chloride content in the concrete cover can help identifying the cause of corrosion. The repair strategy should include repair of concrete in all delaminated areas, the installation of a water proofing membrane, the repair of expansion joints, and necessary upgrading of the drainage system. The concrete repair technique to be adopted, and maintenance program to adopt are briefly discussed.

65. Malhotra, S.K. (1989). **Factors Which Influence Durability of Wooden Structures.** (refer to Environment)

66. Manning, D. (1987). **A Rational Approach to Corrosion Protection of the Concrete Components of Highways Bridges.** Concrete Durability -Katharine and Bryant Mather International Conference, SP-100, American Concrete Institute, Vol. 2, pp. 1527-1547.

The paper traces the development of corrosion protection requirements in Ontario over a thirty year period. Problems of durability of bridges were identified as early as 1963. At that time, however, problems were severe scaling of the concrete. After adoption of air entrainment agents in concrete the problem of durability moved to corrosion of reinforcement. The importance of low permeability concrete and adequate cover is emphasized by the presentation of a chart indicating the number of daily salt application which will lead to corrosion of reinforcement for a given concrete cover and water-cement ratio. The use of membranes have been demonstrated for a long time to improve the durability of concretes exposed to road salts. It is also believed that epoxy coating improves considerably the durability of reinforced concrete. The problems associated with the used of a coated top mat with a black steel bottom mat don't seem to be of concern to the author. It is believed that the large cathode to anode ratio is of significance only if the bare area of coated bars exceeds 0.24 percent and even with that much damaged areas, the service life is projected to be almost 20 times the service life of decks with two mats of uncoated reinforcement. Various components for bridges other than the deck are prone to durability problems due to chlorides. These are the components where chloride contamination can occur from surface runoff, or by splash from adjacent roadway surfaces.

67. Manning, D.G. (1984). **Accelerated Corrosion in Weathering Steel Bridges,** (refer to Case Studies)

68. Maurenbrecher, A.H.P. and R. J. Brousseau (1992). **Review of Corrosion Resistance of Metal Components in Masonry Cladding on Buildings.** NRCC report No. CR-6492.1, August 28.

The report presents a summary of existing information on the corrosion resistance of metal connectors in masonry cladding. The corrosion of the metal connectors is associated with the carbonation of concrete/mortar and chloride ingress. Generally, as the porosity of the mortar increases with increase in water/cement ratio the carbonation becomes more severe. The effect of chlorides in mortar is not well known. It may affect corrosion is various ways: 1) Attract moisture onto metal surfaces; 2) may provide a more corrosive environment by promoting pitting. The authors report rates of corrosion of zinc on connectors in various buildings. Rates of zinc corrosion are based on the measured thickness of zinc at the time of inspection and the age of the building. This assumes that the conditions which led to the deterioration observed at the time of inspection were present throughout the life of the building. It is likely that those

conditions are now more severe than they were (because of the deterioration of the building envelope), indicating an increasing rate of corrosion. (Such predictions of the corrosion rate of zinc can be significantly unconservative when used to predict the remaining life of the component. On the other hand, the rate of corrosion is known to decrease with time under certain environmental conditions. This decrease in corrosion rate with time has been associated to the protective nature of the corrosion products. It is not clear how the authors accounted for the large variation in zinc coating thickness on new connectors in order to estimate the zinc loss.)

69. McLean, R.C., G.H. Galbraith, and C.H. Sanders (1990). **Testing Building Materials - Moisture Transmission Testing of Building Materials and the Presentation of Vapour Permeability Values.** *Building Research and Practice, The Journal of CIB*, Vol. 18, No. 2, pp. 82-91.

The authors present a test procedure to evaluate the differential permeability (permeability under a humidity differential) of building materials. The test materials used were plywood, plaster board, wood, insulation, and brick. The tests showed that for plaster board and polystyrene the permeability is practically constant with changes humidity. However, with wood, plywood and brick, extremely large variations of permeability was observed with the relative humidity. The permeability can be as much as 20 times greater at R.H. of 95% than at low humidity. It was found that, for brick, the permeability only increases slightly at R.H. lower than 75%. However, at R.H. greater than about 75%, the permeability increases rapidly with changes in R.H. A study of the effect of temperature on the measured permeability showed that the temperature effect is negligible. It is the authors' opinion that, despite the fact that much data has been published on permeability of building materials, much of this data are of little use unless the test conditions are reported.

70. Millard, S.G., K.R. Gowers and J.S. Gill (1991). **Reinforcement Corrosion Assessment Using Linear Polarization Techniques.** (refer to Materials)

71. Miller, N.L. and B.W. Cherry (1975). **The Corrosion of Stressing Steel Embedded in Concrete.** Proceedings of the Sixth International Congress on Metallic Corrosion, Sydney, Australia, December, pp. 1496-1502.

The paper presents an investigation of a mechanism for the destruction of the protective nature of the mortar coating together with the development of testing techniques to assess the corrosion state of structures in the field, with particular application to prestressed concrete pipelines. Leaching of calcium hydroxide from the mortar by the action of acidic waters is believed to be the cause of prestressing steel corrosion. It was found that the mortar coating, when subjected to a leaching environment of carbon dioxide bearing waters, appears to show a critical initial permeability below which the densification due to hydration and carbonation is sufficient to protect the inner layers of the mortar coating from the effects of leaching.

72. Morinaga, S. (1990). **Prediction of Service Lives of Reinforced Concrete Building Based on the Corrosion Rate of Reinforcing Steel.** *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 5-16.

The service life of reinforced concrete structures was predicted based on the assumption that the deterioration of the concrete results from corrosion of the reinforcing steel. The life was defined as the point at which the amount of corrosion is sufficient to crack the concrete cover. Corrosion of the rebars is assumed to result uniquely from carbonation of the concrete and chloride ingress. Empirical equations were obtained to predict the rate of corrosion of rebars in a chloride environment as a function of chloride content, water/cement ratio, diameter of reinforcing steel, and thickness of concrete cover. The concrete type (normal weight and light weight) and the orientation of the reinforcing steel were found to have a negligible effect on the rate of corrosion. The effects of temperature, relative humidity and oxygen concentration were investigated separately at various levels of chloride impregnation. Empirical equations were also obtained to predict the rate of carbonation as a function of CO_2 concentration, ratio of carbonation velocity with finished surface to carbonation velocity without finished surface, temperature, relative humidity, water/cement ratio, and time. The rate of corrosion of steel in carbonated concrete was also investigated experimentally as a function of temperature, relative humidity, and oxygen concentration. In general, it was found that the portion of the total life expanded by the carbonation process was significantly greater than the portion of the total life expanded corroding the steel in the carbonated concrete. The carbonation rate was demonstrated to be independent on the chloride content. The life prediction was therefore based on the smaller of corrosion in a chloride environment or the carbonation time. Finally, in order to predict the life of the concrete structure an empirical equation was presented to predict the amount of corrosion required to cause cracking as a function of the concrete cover and the diameter of the reinforcing steel.

73. Oshiro, T., S. Tanikawa, and N. Goto (1991) **A study on Durability of Structures Exposed to Marine Environment.** In *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design.* Proceedings ACI International Conference, Hong Kong, ACI SP-128, Vol. 1, V. M. Malhotra, Ed., pp. 433-447.

A test building was constructed in 1984 and has been exposed to a marine environment under sub-tropical weather for 6 years. A new corrosion monitoring method, developed by Nippon Steel Corporation, was used to monitor corrosion potential, polarization resistance and concrete resistance. The correlation between the corroded area ratio and polarization resistance indicates the possibility to evaluate quantitatively the corrosion of the steel reinforcement in concrete. But there still remains uncertainties and more efforts are needed to clear those uncertainties. The surface coating (acrylic rubber) applied to the experimental building was effective in protecting the steel reinforcement from corrosion due to chloride penetration.

74. Plewes, W.G. (1977). **Failure of Brick Facing on High-Rise Buildings.** Canadian Building Digest, CBD 185, April, pp. 185-1 - 185-4.

Buckling and spalling failures of brick cavity walls and brick veneer cladding on high-rise buildings have occurred in recent years owing to differential movements between the frame and cladding. This occurs as the brick cladding swells in a moist environment while the reinforced concrete frame shrinks and creeps in a relatively dry environment. The author discusses the mechanism of failures and points out common construction features and design details that contribute to problems. Designing to accommodate dimensional changes and attention to details such as ties and anchors is recommended. Reference is made to sources of design data on movements and the strength and installation of ties.

75. Rostásy, F.S. and D. Bunte (1989). **Evaluation of On-Site Conditions and Durability of Concrete Panels Exposed to Weather.** *Durability of Structures,* IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/1, pp. 145-150.

A model for the prediction of durability of concrete panels exposed to weather is presented. The model combines a carbonation law and on-site measurement of the permeability of the concrete cover. The model can be used for quality control or durability assessment of older structures in the course of maintenance. The model presented by the authors is a tentative model and further evaluation is needed. It is assumed that the durability of a structure can be expressed in terms of carbonation of concrete.

76. Sawada, E. (1990). **Repair Method for Salt-Damaged Reinforced Concrete Structures.** *Concrete International,* Vol. 12, No. 3, pp. 37-41.

Coating of the concrete surface is currently attracting attention as a salt damage repair method. The author describes such a system, the Asano Refresh (AR) process, developed by Nihon Cement Co., Ltd. Prepacked aggregate grouted with SBR (styrene-butadiene rubber) or other polymer cement mortar is used when a large part of the concrete cross-section must be replaced. The SBR mortar was found to give particularly good results compared to the other polymers tested. The effect of the polymer cement mortar thickness on the vapor transmission rate and chloride ion penetration was investigated. The system is further improved by the application a surface coating and a salt damage prevention finish material. The system has shown high resistance to chloride ion and water vapor penetration. The performance of the system is not compared with more conventional systems and the performance over time is not discussed.

77. Shiv Kumar, S., R. Heidersbach and J. Lloyd (1986). **The Corrosion of Metal Components in Masonry and Stone-Clad Buildings.** *Proceedings of the Fourth Canadian Masonry Symposium,* Vol. 2, pp. 826-839.

The authors discuss corrosion problems in masonry and stone building facades. References are given for field cases where problems of the exterior facade were traced back to corrosion of steel connectors or anchors. Unfortunately several of the references cannot be found in the journals cited. General recommendations to prevent corrosion related problems are given. "Corrosion control for new buildings should emphasize adequate drainage and selection of coatings or corrosion resistant materials." The authors are not specific on the type of corrosion resistant material to use. A word of caution is given about the use of epoxy injection used to repair cracks. Epoxy injection can lead to increased cracking in some instances. The same can happen from the use of sealants on exterior walls. The causes of that effect are not given.

78. Stockbridge, J.G. (1978). **Evaluation of Terra Cotta on In-Service Structures.** (refer to Case Studies)

79. Swamy, R.N. and R. Jones (1991). **Plate Bonding Technology - The Painless Technique of Structural Rehabilitation.** in *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design*, Proceedings ACI International Conference, Hong Kong, ACI SP-128, Vol. II, V.M. Malhotra, Ed., pp. 1385-1405.

Plate bonding has been used as an effective technique of strengthening reinforced concrete beams in many countries. A review of the role and effectiveness of the bonded plate on the deformation, stiffness, strength and failure behaviour of strengthened reinforced concrete beams is presented. Extensive testing of beams strengthened with bonded plates have shown that plating contributes to a significant reduction of deflection and cracking. High localized stresses are found to exist in the adhesive at the edges of the plate which can lead to premature debonding of the plate. The use of bonded anchor plates was found to be effective end anchorage to the bonded plates enabling the bonded plates to reach yield when the details are properly designed. Tests have shown that significantly damaged beams, when plated in the unloaded or loaded condition, can be restored to stiffness and strength values superior to those of the original unplated beams. Design guidelines are given for the design of bonded plate reinforcement. Emphasis must be placed on close supervision, high quality control and good workmanship on site. Furthermore, regular inspection, and maintenance of steel protection are also essential. The important aspect of durability is not addressed.

80. Takewaka, K., S. Matsumoto and M. Khin (1991). **Nondestructive and Quantitative Evaluation for Corrosion of Reinforcing Steel in Concrete Using Electro-Chemical Inspection System.** In *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design*, Proceedings ACI International Conference, Hong Kong, V.M. Malhotra, Ed., Vol. 1, ACI SP-128, pp. 339-357.

The authors have performed a theoretical and an experimental analysis of the effectiveness of the half-cell potential method for inspection of rebar corrosion. The analysis showed that an approximate corrosion weight loss of reinforcement can be estimated from the potential and concrete resistivity distribution. However, the technique developed by the authors could not be applied to doubly reinforced sections (i.e. slabs with top and bottom reinforcement) because of the galvanic cell formation between the top and the bottom steel (it is impossible to determine whether the estimated weight loss occurs on the top or the bottom steel).

81. Tankut, A.T. and U. Ersoy (1991). **Behaviour of Repaired / Strengthened Reinforced Concrete Structural Members.** in *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design*, Proceedings ACI International Conference, Hong Kong, ACI SP-128, Vol. II, V.M. Malhotra, Ed., pp. 1257-1276.

The authors have investigated the performance of repaired and strengthened members of reinforced concrete structures. (Repaired members are restored to their original strength as opposed to strengthened members which have their original strength increased). Jacketed column behaviour under uniaxial load or combined axial load and reversed cyclic bending was found to be quite satisfactory under the conditions tested if the jacket was made while the structure was unloaded. If the jacket was made under load the performance was rather poor, displaying an axial load capacity of around half of that of a monolithic reference specimen. The behaviour of beams strengthened for flexure under monotonic, repeated, and reversed cyclic loading was found to be successful with the capacity of the strengthened specimens being not less than 90 percent of a reference monolithic specimen. Strengthening by epoxy glued steel plates was found to be much less promising since meticulous work was required to obtain satisfactory behaviour (aging of the system was not investigated). Initial test results on repaired and strengthened slabs showed that the strengthened specimens performed satisfactorily, but the performance of the repaired specimens was rather poor. Reinforced concrete infills were found to increased both the strength and stiffness of reinforced concrete frames. The observed increase in strength was not as large with masonry infills. Finally the strength of epoxy anchorage for rebars in existing concrete was found to be adequate for embedment length of 15 to 20 bar diameters.

82. Thomasen, S.E. and C.S. Ewart (1983). **Techniques for Testing, Analyzing and Rehabilitation of Terra-Cotta.** *Strengthening of Building Structures - Diagnosis and Therapy.* IABSESymposium, Venezia, IABSE reports Vol. 46, pp. 139-146.

The authors discuss observations made during field investigation of terra-cotta failures and tests of the material. The causes of terra-cotta failures have been related to expansion of the material when exposed to moisture, leading to spalling of the glaze, corrosion of ties and anchors, or buckling of part of a facade. In-situ pressure tests can be used to test the terra-cotta anchors. The same frame used for air pressure tests can also be used for water permeance tests. Stresses in various parts of a facade can be measured by mounting strain gauges on the surface and removing a section of the facade on which the strain gauges are mounted. Discussion of the use of lab tests as an assessment tool is also presented. Finally, rehabilitation techniques are briefly discussed. Those include: provision of expansion joints; replacement of corroded or missing

shelf angles and ties; sealing of joints to prevent water penetration; replacement with new terra-cotta or other materials.

83. Thomasen, S.E. and C.L. Searls (1990). **Assessment of Building Facades in Masonry and Stone.** *Service Life of Rehabilitated Buildings and Other Structures,* ASTM STP 1098, S. J. Kelley and P.C. Marshall, Eds., American Society for Testing and Materials, pp. 108-116.

Original building enclosures and past restorations and repairs to building facades require periodic evaluations to assess their safety, durability, performance, and aesthetics. The authors discuss inspection techniques (non-destructive and destructive) used to assess the condition of building facades. Visual inspection should be used to determine the location where invasive inspection should be practiced. The use of inspection openings and a fiber-optic borescope is recommended to minimize damage to building facades. A pachometer can be used to determine the location of masonry ties. A copper-copper sulfate half cell can then be used, with an electrical lead connected to a tie or metal conductor backup, to assess the corrosion activity in the wall ties. (If the ties are not attached to a conductive backup the technique is of limited use since each tie would have to be exposed to connect the electrical lead). Field monitoring is also important to assess whether cracks are still moving or stopped. The authors also discuss some destructive field tests. The use of lab test is advocated to determine the compatibility of repair materials with existing materials. Accelerated lab tests are also recommended to assess the durability of new materials for which previous service records are not available.

84. Vaysburd, A.M. (1993). **Some Durability Considerations for Evaluating and Repairing Concrete Structures.** *Concrete International,* Vol. 15, No. 3, pp. 29-35.

The author presents, among other things, a fairly long discussion of the effect of chlorides on corrosion of steel in reinforced concrete structures. A better discussion of the same subject has been presented by Pfeifer et. al. (1992). The existence of a chloride threshold level is not believed to exist (this is repeated several times). The effect of cracking of concrete on the durability of reinforced concrete is also discussed. It is believed that localized cracking is not detrimental to corrosion of reinforcing steel since only small quantities of corrodents can access the steel. However, if cracking is widespread to the point where the permeability of concrete is increased the durability of the reinforced concrete will be affected. It is also believed that a good bond between the steel and the concrete is essential to prevent the accumulation of corrosion products and to ensure proper protection from the concrete (corrosion is not believed to take place when good bond is maintained). The problem here is that bond is usually broken when corrosion starts, so one can ask: "is debonding the cause or the result of corrosion?" The paper is interspersed with little 'glitches' such as the misconception that the corrosion film on rebars in alkaline concrete passivates the underlying steel (it is the corrosion layer that is passive and it protects the steel), etc...

85. Yuan, Y.S. and M. Marosszeky (1991). **Major Factors Influencing the Performance of Structural Repair.** *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design.* Proceedings ACI International Conference, Hong Kong, ACI SP-128, V.M. Malhotra, Ed., Vol. II, pp. 819-837.

An experimental investigation of the performance of structural repair on reinforced concrete is presented. Beams with preformed cavities to simulate spall were cast and three types of polymer modified concrete were used as repair material. The test results showed that the effect of shrinkage of polymer cement concrete on the stress and serviceability of a repaired structure is quite significant. The restrained shrinkage can lead to cracking in the repair patch and to additional tensile stresses in the substrate. Acrylic modified concrete was found to behave less favorably than styrene modified concrete. SBR showed expansion during the first 24 hours and low shrinkage strain subsequently. Consequently, SBR did not show cracking. Tests and analyses showed that the major factors influencing the performance of structural repair include free shrinkage, creep coefficient and tensile strength and ultimate tensile strain in early age properties of the repair material. Stiffness of the member and moment redistribution in the repaired structure are also important.

Service Life Prediction

1. Akoz, F. and M.S. Akman (1990). **Service Life Estimation for Multi-Ply Flat Roof Membranes.** (refer to Components and Assemblies)

2. Andrade, C., C. Alonso, J.A. Gonzalez, and J. Rodriguez (1989). **Remaining Service Life of Corroding Structures.** (refer to Materials)

3. Androic, B., S. Juric, and D. Dujmovic (1989). **Checking the Reliability and Durability for Corrosion.** *Durability of Structures*, IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/2, pp. 859-864.

   The authors discuss the decrease of the safety index which takes place with time under fatigue loading. As expected, the decrease in safety index is more accentuated when corrosion fatigue is considered. The reduction in fatigue strength due to the presence of corrosion is only assumed. Reductions from 0 to 50 percent have been assumed. Curves of safety index vs. time are presented which can be used to estimate the required safety index for the new structure given the desired service life and the effect of corrosion in reducing the fatigue strength.

4. Borges, J.F. (1989). **Some Basic Concepts in Building and their Relationship to Durability.** in *Durability of Structures*, IABSE Symposium, Lisbon, Sept. 6-8, Vol. 57/1, pp. 3-14.

   The basic concepts of 1) essential requirements and performance criteria, 2) quality assurance and human error, 3) probabilistic reliability and safety differentiation, 3) liability and technical insurance are briefly introduced and their relationship to durability is discussed. It is concluded that, when applied to buildings, the essential requirements (safe, serviceable and durable) may be enlarged to become healthy, intelligent and friendly. It is also concluded that to achieve quality, and implicitly durability, standard quality assurance procedures should be followed. The theory of probabilistic reliability may be extended to cover deterioration models also. The differentiation between theoretical and effective probabilities of failure is that the effective probability reflects human error. Finally, the author concludes that the present tendency to resort more and more frequently to liability claims based on negligence should be denounced.

5. British Standard (1992). **Guide to Durability of Buildings, and Building Elements, Products and Components.** (refer to Components and Assemblies)

6. Browne, R.D. (1982). **Design Prediction of the Life for Reinforced Concrete in Marine and Other Chloride Environments.** (refer to Components and Assemblies)

7. Clifton, J.R. (1990). **Methods for Predicting the Service Life of Concrete.** *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 361-373.

   The author discusses methods for predicting the service lives of new concrete. The methods discussed are: 1) estimates based on experience (does not form a reliable basis for service life prediction); 2) deductions from performance of similar materials (comparisons between the durability of old and new concretes is not straightforward), 3) estimates based on the results of accelerated testing (an important requirement for using accelerated testing is that the degradation mechanism in the accelerated test should be the same as that responsible for the in-service deterioration), 4) applications of reliability and stochastic concepts (service life models using stochastic methods are based on the premise that service life cannot be precisely predicted), and 5) mathematical and simulation modelling based on the chemistry and physics of degradation processes. This is a good paper which provides a clear picture of the present state of the art in the area of service life prediction.

8. Fagerlund G. (1985) **Essential Data for Service Life Prediction.** In *Problems in Service Life Prediction of Building and Construction Materials* (ed. L.W. Masters), Martinus Nijhoff Publishers, Dordrecht, pp. 113-138.

   The author shows that durability based upon old experience-codes of good practice is a dangerous method that can lead to a lot of durability problems, especially when dealing with new materials or proven materials in new applications. It would be preferable if the qualitative concept "durability" was abandoned in favour of the quantitative concept "service life". The use of the service life concept in design means that the traditional accelerated test methods must be abandoned in favour of non-accelerated tests. The problems with accelerated tests are: it is almost always impossible to translate the exposure time in the test to a real exposure time in the real environment; the acceleration sometimes changes the destruction mechanisms and, consequently, the test results will bear no resemblance to the real behaviour; the acceleration is sometimes so large that destruction occurs although it would not occur in practice; the synergistic effect often observed between two or more destructive actions cannot be revealed when only one destruction mechanism is studied.

The service life prediction should be based on stochastic analysis of the factors influencing the destruction mechanisms. The effect of uncertain material or environmental data on the service life can always be analyzed by a sensitivity analysis. The author presents a list of information necessary for a service life prediction.

9. Frohnsdorff, G. and L. Masters (1990). **Suggestions for a Logically-Consistent Structure for Service Life Prediction Standards.** *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 113-126.

The methodology for service life prediction, ASTM E-632 and RILEM Recommendation No. 64, are too general to give detailed guidance on their application to individual items. The author proposes a hierarchy of codes, with the more general codes at the top, to give more specific guidance for the evaluation of the service life for different materials in various environments. Standards should be provided for the characterization of the environment, for the characterization of the materials, components, and systems, for the determination of the mechanisms and kinetics of degradation, for mathematical models of degradation, and for service life prediction. The author also presents a general methodology for service life prediction applicable to any item.

10. Frohnsdorff, G. and L.W. Masters (1978). **The Meaning of Durability and Durability Prediction.** First International Conference on Durability of Building Materials and Components, ASTM STP 691, pp. 17-30.

The authors discuss the meaning of the term durability. They point that durability is not an absolute quality of an item but a term expressing a human perception of a quality which changes with the environment. It implies likelihood of lasting well in expected environmental exposures. The ASTM definition of durability is presented. The definition incorporates the concept of design requirements being met or exceeded for a specific period of time such as the design service life. The authors discuss some of the problems of service life prediction from standard durability tests. A more detailed discussion of the ASTM recommended practice for development of accelerated tests for the prediction of service life is presented. Two practical examples (coating for steel protection and concrete exposed to a sulfate environment) of the use of the recommended practice are presented. The examples outline the procedure to use to design and interpret accelerated test results used for service life prediction. It is emphasized that, in order to predict the service life, one must define the nature of the material, characterize the nature of the environment, and have a good knowledge of the deterioration mechanism. The authors recommended that reliability concepts should be used in service life prediction.

11. Haagenrud, S.E. (1985). **Mathematical Modelling of Atmospheric Corrosion and Environmental Factors.** (refer to Materials)

12. Haagenrud, S.E., V. Kucera, and J. Gullman (1982). **Atmospheric Corrosion Testing by Electrolytic Cells in Norway and Sweden.** in *Atmospheric Corrosion*, W.H. Ailor, Ed., John Wiley and Sons, New York, pp. 669-694.

The electrochemical technique is based on measurement and integration of the current in electrolytic cells with an external imposed d-c voltage. The use in several applications is described, i.e., the influence of environmental parameters on the cell current and time-of-wetness, comparative studies of corrosion properties of different alloys, and analysis of the corrosion environment in an industrial plant. The possibilities and limitations of the technique are discussed.

13. Harrison , W.H. and M.E. Gaze (1989). **Laboratory-Scale Tests on Building Mortars for Durability and Related Properties.** (refer to Materials)

14. Hookham, C.J. (1992). **Service Life Prediction of Concrete Structures - Case Histories and Research Needs.** (refer to Case Studies)

15. Ishizuka, Y. (1983). **The Degradation and Prediction of Service Life of Building Components.** *Durability of Building Materials*, Vol. 1, No. 4, pp. 345-352.

The Government Building Department of the Ministry of Construction in Japan conducts a field survey of the state of concrete and steel buildings every five years. The survey is intended to provide a 'degradation index' of structure, building components and materials, individually. The service life prediction of buildings is based on a statistical analysis of the buildings of the same age across the country. The values of the degradation indices for the same structural components of the same age over the country was found to follow a normal distribution. The statistical method developed for the prediction of service life accounts for the difference due to the conditions of climate and site.

16. Legget, R.F. and N.B. Hutcheon (1958). **The Durability of Buildings.** *Symposium on Some Approaches to Durability in Structures*, ASTM STP No. 236, American Society for Testing and Materials, pp. 35-44.

A general discussion of the durability of buildings, its definition and implication on the design, is presented. "There is no such thing as the durability of a building, the durability of the major components of a building being inevitably different". The term "service life" should be used instead of the vague and indefinite word "durability".

17. Lipfert, F.W. (1987). **Effects of Acidic Deposition on the Atmospheric Deterioration of Materials.** (refer to Materials)

18. Lipfert, F.W., M. Benarie, and M.L. Daum (1986). **Metallic Corrosion Damage Functions for Use in Environmental Assessments.** (refer to Environment)

19. Lucchini, A. (1990). **Models for the Evaluation of the Service Life of Building Components.** In *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 615-624.

The author presents a proposed logistic for the evaluation of the service life of a structure. The procedure for the evaluation of the service life proposed by the author can be summarized as follows: 1) define the environmental characteristics and the various materials in the component of the structure considered; 2) define the performance specifications and the functions of the material relevant to the system; 3) for each material obtain the models describing the response of the material to the environments. After this stage experimental investigation may be necessary to define the analytical models necessary to predict the material response; 4) the analytical evaluation of each system (materials/environment) and identification of the critical function (material property) - critical material; 5) service life prediction.

20. Lucchini, A. (1990). **An Approach to Design for Durability of the Building Technological System.** In *Durability of Building Materials and Components*, Proceedings of the Fifth International Conference held in Brighton, U.K., 7-9 November, pp. 477-483.

The paper introduces an approach to design for durability of the building technological system based on the theory of disturbance factors. The disturbance factor is defined as the factor triggering anomalies in the functioning (reflected by the structure's behaviour at time t=0) or evolution of the over time behaviour of a building component leading to shortening of the service life.

21. Morinaga, S. (1990). **Prediction of Service Lives of Reinforced Concrete Building Based on the Corrosion Rate of Reinforcing Steel.** (refer to Components and Assemblies)

22. Philipose, K.E., R.F. Feldman, and J.J. Beaudoin (1991). **Durability Predictions from Rate of Diffusion Testing of Normal Portland Cement, Fly Ash, and Slag Concrete.** (refer to Materials)

23. Pihlajavaara, S.E. (1984). **The Prediction of Service Life with the Aid of Multiple Testing, Reference Materials, Experience Data, and Value Analysis.** Third International Conference on the Durability of Building Materials and Components, Espoo, Finland, August 12-15, Vol. 1, pp. 37-64.

The author presents a strategy to evaluate experimentally the durability of new materials. When a material is tested under accelerated condition, it is important to test a reference material in order to be able to correlate the accelerated test conditions with the actual environmental conditions. Before engaging in a long-term test program, preliminary tests should be designed to eliminate the materials which do not have potential to be durable under long term conditions. The prediction of service life from the analysis of the values obtained from accelerated tests on the new material and the reference material, and correlation of the real environment with the accelerated test environment is discussed. The service life must also be defined statistically or in terms of the permissible amount of inferior material quantity or specimens.

24. Raharinaivo, A., P. Brevet, G. Grimaldi, and G. Pannier (1986). **Relationships Between Concrete Deterioration and Reinforcing Steel Corrosion.** (refer to Materials)

25. Rostásy, F.S. and D. Bunte (1989). **Evaluation of On-Site Conditions and Durability of Concrete Panels Exposed to Weather.** (refer to Components and Assemblies)

26. Sentler, L. (1987). **Service Life Predictions of Concrete Structures.** *Durability of Building Materials*, Vol. 5, No. 1, pp. 81-98.

The author discusses the use of stochastic methods to predict the service life of structures. The change in material properties such as the permeability of concrete is described as a function of loads and time. The stochastic model for the effect of load on the permeability of concrete evolved from creep tests whereby the strain in concrete changes with time. The effect of load level and environment on the deterioration rate of concrete and steel is discussed. The combined effect of load and environmental agents is also presented. In order to relate the loads and environment to the deterioration of a structure the relation between loads and load effects and between environment and micro-climate must be considered.

27. Shirayama, K. (1985). **Research Activities and Administrative Measures on Durability of Buildings. The State of the Art in Japan.** *Matériaux et Constructions / Materials and Structures*, Vol. 8, No. 105, May-June, pp. 215-221.

The author presents a summary of the research work performed in Japan on the durability of structures over the past century. A significant increase in the number of papers on durability and service life has been observed in the Japanese literature since 1965. In 1979 a committee was established to systematize the concept of durability. The first task of this committee was to define the terminology related to the field of durability. A sub-committee then proceeded to prepare principles for the process of planning for durability. Work was carried out between 1973 and 1978 to develop a procedure for predicting the service life of dwellings and their components. An extensive research project initiated in 1980 is dealing with the development of techniques for improving service life of buildings. The concept of service life being the important factor, research has been conducted to develop systems for more flexible buildings (the change in building use must be anticipated at the design stage). The author mentions two important projects launched with the purpose of providing housing with such flexibility. Other projects initiated in the '80's are dealing with improvement of durability of materials and buildings, and development of non-destructive testing techniques. Nation wide efforts are also directed at administrative measures to improve durability. One such example is long term guarantee system.

28. Siemes, T. and T. Vrouwenvelder (1985). **Durability - A Probabilistic Approach.** *Durability of Building Materials*, Vol. 3, No. 1, pp. 101-113.

The scatter in observed service life of building structures is very high. The authors present an investigation of the use of reliability analysis to aid optimization of design for durability. Essentially the same techniques are used as those which were proven to be successful in design for ultimate and serviceability limit states without deterioration effects. The results of a survey of carbonation effects on outdoor gallery slab (concrete cover, maximum-mean depth of carbonation, etc...) are presented in the form of a mean value and a coefficient of variation. This shows how can various alternative constructions can be compared in terms of expected capitalized costs. From a sensitivity analysis the variables that are mainly responsible for the scatter in the service life can be identified. The technique of service life prediction and capitalized cost evaluation seems be a promising tool for the decision making in the design of new structures, repairs and renovations.

29. Siemes, A.J.M., A.C.W.M. Vrouwenvelder, and A. van den Beukel (1985). **Durability of Buildings: A Reliability Analysis.** *Heron*, Vol. 30, No. 3, pp. 1-48.

This paper is a more detailed version of the above paper by Siemes and Vrouwenvelder (1985). Worked out examples of service life calculation and life cycle cost analysis illustrate the practical use of reliability analysis in durability assessment.

30. Siemes, A., A. Vrouwenvelder and A. van den Beukel (1985). **Stochastic Modeling of Building Materials Performance in Durability.** *Problems in Service Life Prediction of Building and Construction Materials*, L.W. Masters, Ed., Martinus Nijhoff Publishers, pp. 253-263.

This is the same material as presented in the above two papers. No new information is presented.

31. Singh, G. (1991). **The Promise and Challenge of Evaluation of Service Life.** in *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design*, Proceedings ACI International Conference, Hong Kong, ACI SP-128, Vol. II, V. M. Malhotra, Ed., pp. 1423-1437.

A general introduction is followed by justification of the need for and benefits of evaluation of service life of structures. A probabilistic simulation (using Monte Carlo technique) approach implemented in a computer program is presented to evaluate the service life distribution of a structure once the deterioration model is

established and the statistical distribution of the variables involved is known. A sensitivity analysis is also performed to determine which of the model parameter has a greater influence on the service life. Models for life-cost analysis are also presented. The methodology presented calls for research and developments towards understanding of the fundamental time-dependent mechanisms of degradation. Herein lie the promise and the challenge. In the author's view other methods such as estimates based on past experience, estimates through comparison, extrapolation of accelerated testing and statistical analysis of past data without consideration of mechanisms, cannot yield reliable estimates on their own.

32. Sjöström, C. (1987). **A View on Building Materials Durability Research: Activities at the National Swedish Institute for Building Research.** *Durability of Construction Materials*, Proceedings of the First International Conference held by RILEM, Versailles, France, Sept. 7-11, pp. 915-918.

The major part of the research at the Materials and Structures Division is concerned with a long-term performance under in-use conditions of building materials and components. The central theme in research on the durability of building materials is to create knowledge and methods for reliable predictions of service life. An important element which is often lacking in service life studies is feedback of the performance of materials in service. The Institute has developed methods for statistical surveys of the technical properties of the building stock. Projects on the long-term performance of loose-fill thermal insulation are carried with special attention given to the settlement of loose-fill materials. Some studies have looked at the material properties changes with time compared to those values assumed at the design stage. The author mentions that the development of measurement techniques and measurements/descriptions for in-use environments ought to be important research areas within building materials durability research. The paper reveals very little about the nature of the research being done at the Institute and is somewhat philosophical rather than factual.

33. Sjöström, C. (1985). **Overview of Methodologies for Prediction of Service Life.** *Problems in Service Life Predction of Building and Construction Material,* L.W. Masters, Ed., Martinus Nijhoff Publishers, pp. 3-20.

The author presents an overview of some proposed or used methodologies for approaching research on the service life of building materials and components. To provide a more general approach to durability testing an ASTM committee has prepared a standard for developing accelerated tests to aid prediction of service life (ASTM E632). This standard acted as a model for other methodologies such as the ones used by the Centre Scientifique et Technique du Batiment (CSTB) and the National Swedish Testing Institute. Other methodologies have been proposed by RILEM TC-60 CSC, the Australian Standard 1745 and, CIB working commission W60. A common aspect of the various approaches is the importance of identifying the degradation mechanisms and the need for comparing the results from predictive service life tests or artificial aging with the findings from long term tests under service conditions. A generic methodology has been proposed in the draft report of the CIB W80 / RILEM 71-PSL Committee. General research needs are outlined. Among the most urgent are: the gathering of in-service performance data through field inspection of buildings; development of procedures for feedback of the performance of materials under in-use conditions; development of methods for inspecting the state of existing buildings to assess the remaining service life; work to increase the knowledge of microenvironment and of the interdependence of micro-, meso- and macroclimates; development of mathematical models for the observed degradation.

34. Sneck, T. (1981). **RILEM and Durability.** *Matériaux et Construction / Materials and Structures*, Vol. 14, No. 83, pp. 379-390.

The author presents a summary of the discussion that took place during the September 22-23, 1980 RILEM meeting. In the report the concept of durability is elaborated in general terms and the contributions and the discussion at the meeting are reviewed. The report is divided into seven sections. After a brief introduction the author presents a general background in which performance aspects are discussed as well as the concept of durability and definitions of terms are given. The close relation between durability and performance over time is discussed. The third section explains why there is an interest in durability and discusses economic implications. A need to disseminate the information presently available is recognized. The fourth section discusses the existing techniques to evaluate the performance of materials, components, and structures. The need for feedback of the performance of materials in service is stressed. Although data collected from field failures are important, there is a need to develop methods for inspecting the state of existing buildings showing no sign of distress. The fifth section gives a description of the past and present RILEM activities. Section six identifies areas where work is needed. Those are the performance over time of exterior and interior building components, elements, bearing structures, and materials for heat and moisture insulation. The author points the need for better methods of field data collection, the characterization of in-use environment and relations between short term test results and field performance. Finally, section seven gives a summary. All the RILEM committees are asked to be aware of the importance of durability problems and try to integrate them in their studies.

35. Somerville, G. (1992). **Service Life Prediction - An Overview.** *Concrete International,* Vol. 14, No. 11, pp. 45-49.

The author presents an overview of service life prediction of structures. Looking at past experience, the author states that aggressive actions (chlorides, sulfates) are the loads to use in the development of a viable design method for service life based on degradation models. The microclimate is identified as the critical factor in degradation of materials. A short discussion of what should be a satisfactory in-service performance is presented. Performance should include function in use, financial consideration and technical provisions. A discussion of current design methods for service life (concrete cover, crack control) relying on concrete technology approach, is presented. In addressing the future developments, the author states that the greatest concern should be with corrosion, and the most pressing needs are to bring together all current developments concerned with durability and to convert the available information into design format. "If we recognize the transportation mechanisms created by water, wind, and temperature, then by good design and a combination of architectural and structural detailing, we can prevent or significantly reduce the risk of aggressive actions reaching critical areas."

36. Soronis, G. (1992). **The Problem of Durability in Building Design.** *Construction & Building Materials,* Vol. 6, No. 4, pp. 205-211.

The paper is said to be a state of the art report in the area of design for durability. It is mostly based on the proceedings of the International Conferences on the Durability of Building Materials and Components held between 1978 and 1990. The paper emphasizes the need of a technology and knowledge transfer between the research scientists and designers. The volume of material published on design for durability is too overwhelming for designers to take the time to study the available material. Definitions are given for terms related to the design for durability. Some of the defined terms are durability, deterioration, performance over time, design life, economic life, macro-, meso-, and microclimate. Factors which need to be accounted for in order to achieve an optimum design are discussed (those are design and functions, design and environment, design and materials, and design and economy). The most urgent research needs are listed as: to develop an internationally accepted, systematic, functional and performance-oriented methodology to facilitate the design process; to develop computerized systems aimed at giving designers decision making information; to develop practical guidelines for authors of scientific publications so that they might interpret their scientific results in a way which more closely meets the needs of building designers. The author presents guidelines to help authors of scientific papers to convey information for durability to building designers.

37. Spence, J.W. and F.H. Haynies (1988). **Theoretical Damage Function for the Effects of Acid Deposition in Galvanized Steel Structures.** (refer to Materials)

38. Theophilus, J.P. and M. Bailey (1984). **The Significance of Carbonation Tests and Chloride Level Determination in Assessing the Durability of Reinforced Concrete.** Third International Conference on the Durability of Building Materials and Components, Espoo, Finland, August 12-15, Vol. 3, pp. 209-238.

The significance of carbonation and chloride concentration in concrete is established by a brief discussion of the mechanism of corrosion of metals embedded in concrete. The authors outline various methods of determining the depth of carbonation in concrete. Of all the techniques reviewed the use of acid/base indicator phenolphthalein is found to be the most practical and was found to be accurate when compared to other methods. Various methods of determining the chloride content in concrete are enumerated. The total chlorides within the concrete can be evaluated by titration of a nitric acid extract or other rapid chemical techniques more suitable for field use, x-ray fluorescence. Since chloride content is usually specified as a percentage of cement content, methods of determining the cement content are also discussed. From a study of the accuracy of the various techniques, it seems that the chemical titration technique is preferred.

39. Thielen, G. (1983). **Implementation of Durability Related Specifications in Technical Guidance Documents.** *Durability of Concrete Structures,* CEB - RILEM International Workshop, S. Rostam, Ed., 18-20 May, Copenhagen, pp. 327-339.

The paper tries to setup a conceptual frame and to discuss technical details concerning the implementation of information on durability in technical guidance documents such as codes and recommendations guiding design, construction and repair of concrete structures. The author introduces the concept of structural performance. The performance concept necessitates to classify the information in 4 categories: requirements (safety, serviceability, structural appearance); criteria upon which the requirements are to be satisfied (safety criteria could be stability, strength, fatigue resistance, ductility, etc..); assessment and practice where all information must be compiled which is necessary to achieve in practice the required level of durability. The author recognizes that experience still forms an important basis for engineering decisions concerning durability, although the use of new materials or existing materials in new environments will limit the value of experience. It is believed that analytical models and calculation methods will become more important in the evaluation of durability.

40. Tuutti, K. (1980). **Service Life of Structures with Regard to Corrosion of Embedded Steel.** (refer to Materials)

41. Van Court, D.P. (1978). **The Owner / Tenants Interest in Unifying Durability Data.** First International Conference on Durability of Building Materials and Components, ASTM STP 691, pp. 71-76.

The author advocates the development and the use of unified tests for different building materials. Presently, different tests are used for different building materials, making it difficult to compare various materials, especially when new materials are involved. Unified testing techniques for different materials would enable the owner / tenants and the designers to select the most efficient material for any given job. The author does not make any recommendation on the procedure to adopt to develop such unified test. (Note: although desirable from an economic and environmental point of view, the development of unified tests is very complex because different materials have different deterioration processes affected by different factors).