REFERENCES:

/1/ DANISH MINISTRY OF TRANSPORT:
Concrete Durability
Bridge division May 1980

/2/ PLUM N.M.:
Foreløbig vejledning i forebyggelse af skadelige alkalikiselreaktioner i beton. (In Danish)
SBI København 1961

/3/ ROMER B.:
Angewandte Mikroskopie bei der Baustoffprüfung, Beispiel Beton.
Strassen und Tiefbau. Heft 5 1974

/4/ ASTM C 227

/5/ CHATTERJI S.:
An Accellerated Method for the Detection of Alkali-Silica Reactivities of Aggregates.
Cement and Concrete Research 8.
647-650, 1978.

/6/ ÓLAFSSON HÁKON & THAULOW NIELS:
Alkali Silica Reactivity of Sands
Nordtest Project 179-79.
The Building Research Institute
Reykjavik 1981.

/7/ ASTM C 289

/8/ SMOLCZYK H-G.:
Prüfung und Beurteilung von Betonzuschlag.
Schriftreihe der Zementindustrie
Heft 40. Düsseldorf 1973

/9/ SØNDERGÅRD B.:
Petrographic Investigation of Quaternary Danish Gravel Deposits.
Progress Report E1. SBI 1959
Copenhagen

DETERIORATION OF CONCRETE STRUCTURES IN SOUTH WEST ENGLAND: THE USE OF CRACK MAPPING AS AN INVESTIGATORY TOOL

C D. Comberbach, Industrial Geologist, E.C.C. Quarries Ltd., Exeter, U.K.
Prof. P.G. Fookes, Consulting Engineering Geologist, Caterham, U.K.
J.Cann, Geologist, Engineering Geology Ltd., Godalming, U.K.

ABSTRACT

For the purpose of mapping deteriotiation of concrete, cracks can be classified into two groups; non-progressive and progressive. Each form of deterioration can be characterised by a particular crack pattern and other surface features.

A programme 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. One structure, a multi-storey car park, was chosen for detailed study. The types of crack patterns were diagnosed by mapping and testing selected members in detail. The results were extended to a classification survey of the whole structural frame of the car park which aided the establishment of trends in deterioration. Details are given of how a simple coloured summation map was constructed to highlight areas which were in need of immediate attention. The widespread occurrence of alkali- silica reactivy and reinforcement corrosion was of particular significance.

A classification survey of the other structures, which were made of materials similar to those used for the car park, provided data which was plotted as a graphical relationship between age and condition. From this, a speculative trend envelope for the local rate of deterioration was established for structures with alkali-silica reactivy in south-west England.

FIELD INVESTIGATIONS

CRACK MAPPING

1. INTRODUCTION

1.1. Earlier investigations of concrete structures have generally aimed at collecting information on the durability characteristics and the various types of any deterioration present. Results of investigations have enabled decisions to be made on the needs for maintenance and/or repairs of affected structures. The following list outlines the various procedures that have been applied, in full or part, during many investigations:

(a) Compilation and evaluation of data on initial concrete quality

(b) Visual examination of the field behaviour of the concrete

(c) Exploration of the environment and exposure conditions to which the structure is subjected.

(d) Detailed examinations of concrete materials and of concrete specimens

(e) Supplementary tests on the concrete in situ

(f) Supplementary laboratory tests

1.2. Dr. G.M. Idorn has been a pioneer of survey inspections of concrete structures, particularly in Denmark, since the 1950s. It was then that he realised that inspections would be better for utilising comprehensive survey data than the somewhat sparse data collected by his predecessors./1/

1.3. The extent and significance of deterioration which should be considered in relation to a particular structure and its function can be estimated in various ways. Site inspection of the structure can be combined with macroscopic (hand specimen) and microscopic (thin section) examinations, together with physical and chemical tests of lump samples and/or cores drilled from the structure. In addition to deterioration, the future operational capacity and competence of the structure may have to be evaluated.

1.4. As concrete deteriorates the processes often manifest themselves by cracks and other features which are characteristic of the particular mechanism of deterioration. This usually makes it possible to determine the causes of the deterioration by careful observation of surface features. However, several crack patterns may be present on the same concrete surface, so the total amount of cracking at any one time resulting from each mechanism may have to be proportioned. A further requirement is to decide whether deficiencies are likely to become worse or remain relatively stable/2/3/.

1.5. For this purpose crack types can be divided into non-progressive and progressive. The non-progressive group includes plastic shrinkage, plastic settlement crazing and thermal hydration shrinkage. These cracks do not develop significantly longer, deeper or wider with time. Progressive cracking includes drying shrinkage, structural distress, reinforcement corrosion, forms of alkali-aggregate reactivity, frost attack, chemical sulphate attack and physical salt weathering. These may progress to an extent that the performance of the structure is affected and remedial measures required.

1.6. The main purpose of this paper is to outline some field survey investigations which can be undertaken. These include a field classification system of a complete concrete structure, and detailed mapping of individual members as required. Although this type of survey does not replace laboratory techniques, it may help to utilise more fully and reduce expensive coring. Laboratory analyses may be necessary in helping determine the cause of deterioration, but are less likely to aid the determination of the rate and extent of deterioration. Ideally a full investigation

should include a balance of field observations and laboratory tests. Laboratory aspects of this study are not discussed further in this paper.

1.7. Earlier works described the application and value of crack mapping techniques during investigations of deteriorated concrete structures in the Middle East/3/4/. A similar approach was adopted during the investigation of various structures in south-west England, all of which were known or thought to be suffering from the effects of alkali-silica reactivy. One structure, a multi-storey car park, was chosen for detailed study, as outlined in Section 2 below. Observational judgements were made on another eight structures with a view to making speculative preliminary predictions on the rate of deterioration due to local alkali-silica reactivity. For further details of the occurrence of alkali-aggregate reactivy in the United Kingdom see references /5/ and/6/.

2. FIELD INVESTIGATION PROCEDURES

2.1. Desk study and walkover survey of the car park

The initial part of the investigation consisted of a small desk study of structural and contract specifications. The information obtained from the desk study supplemented a preliminary walkover survey of the whole structure. This allowed a general assessment to be made in terms of the following:

(a) The types of structural members and their general positions.

(b) Workmanship and evidence of the condition of the concrete at the time of placing; important features included mix type, surface laitance, evidence of bleeding, honeycombing, voids, deformation, evidence of plastic movement, segregation, structural joints, impressions of the shuttering and the general finish.

(c) Evidence of deterioration of the hardened concrete such as crack patterns, crack type and style, and location of the most severely affected members. Areas exposed to the weather and to water running along expansion joints or faulty drains were found particularly susceptible. Features such as discolouration, exudation, surface weathering, spalling, surface softening, dampness, popouts, pitting, rust staining, abrasion and encrustations also provided evidence on the condition of the concrete.

(d) The local environment - situated near the south coast of south-west England which is generally fairly well exposed with relatively damp warm summers, cool winters and prevailing westerly winds.

2.2 Classification mapping

2.2.1. Each individual member of the cast in situ concrete frame was classified by visual observation to characterise its condition. This was done in conjunction with detailed mapping of selected members (see 2.3). Classification by scoring was made under several headings on a scale of 1-5. Half values were used where a more refined assessment was possible. The classification was devised mainly for alkali-aggregate reactivity but was flexible enough to be extended to cover other types of deterioration. It attempted to take into account all significant factors which had affected the performance of the concrete.

2.2.2. The classification scheme is summarised in Tables 1, 2 and 3. It is intended to provide a useful means of rapid, semi-quantitative analysis of concrete structures during a field survey. It is generally important that the structure is classified by each separate concrete pour, since the variables in the scheme will differ from one pour to the next.

2.2.3. Classification maps were built up on appropriate design drawings using the data from the field investigation. Several maps, each one displaying the results from one or more aspects of the classification (eg, degree of exposure), were produced in order to avoid the necessity for a complex coding system.

2.2.4. To identify quickly areas for further study and to help define areas possibly needing remedial works, it was necessary to draw up a simple coloured summation map to include all the observations. In order to implement this it was decided that the scores in each group heading in the classification scheme should be multiplied by a factor of 1, 2, 3, 4 or 5, to emphasise those groups which were considered to have the most important effect on the risk of further deterioration of the structure. Those considered the most important were multiplied by the maximum of 5. The least important groups were not increased at all. These factors, which are somewhat arbitrary, were decided upon during the survey and are to be the subject of further study.

2.2.5. The group headings, crack description, concrete type and structural function were considered exceptional. Excluding these, the sum of the scores given to each of the other group headings for a particular member was calculated. More score points were then added to the total, depending on crack description, concrete type and structural function. The system is explained more fully in Table 4.

2.2.6. The maximum number which could be assigned to any concrete member was 100 points and the minimum 19. The higher the number of points, the more serious is the condition of the member and the higher the risk factor.

2.2.7. The summation map was then built up by dividing the total score points into a series of groups, to indicate different stages of increasing risk of further deterioration. Each member was then re-classified on this basis and the appropriate part of a large scale design drawing of the

TABLE 1: Classification scheme used for mapping of concrete structures in south west England

GROUP HEADING	CLASS		COMMENTS
	SCORE	DESCRIPTION	
Position	-	-	The exact location of the member of interest with reference to permanent points on the structure e.g.numbered columns.
Degree of exposure	1 2 3 4 5	Completely protected Slightly exposed Moderately exposed Highly exposed Completely exposed	For this study it was sufficient for the term "exposure" to refer to the cool/warm damp climate of south west England rather than to specific environments, for example, wet earth. However, the presence of faulty drains or excessive leakages was taken into account wherever present.
Degree of cracking	1 2 3 4 5	No cracking Minor cracking Moderate cracking Overall cracking Severe overall cracking	The term "cracking" is taken to include other features such as spalling and popouts.
Crack description, geometric and generic	-	-	A brief, accurate description of the crack pattern(s) and diagnosis of the causes. Estimate percentages of each type of deterioration present. Use in conjunction with Tables 2 and 3.
Concrete type	-	-	Note whether the concrete has been re-inforced and cast insitu or otherwise. Take small hand sample for inspection of aggregates and cement paste. Estimate relative w/c ratio of the member, by visual observation, on a scale of 1-5.
Workmanship	1 2 3 4 5	Very good Good Moderate Poor Very poor	Features which include surface crazing, honeycombing, segregation, voids, steel alignment (where visible), poor compaction and shuttering, cold joints and patched up concrete should be noted.
Structural Function	-	-	Note the structural significance of the member of interest, e.g. floor edge beam, parapet wall.
Exudation	1 2 3 4 5	No exudation Light exudation Moderate exudation Heavy exudation Severe exudation	Includes carbonated cement paste con-stituents, gel, damp areas and rust; i.e. substances which actually "flow" from cracks or voids
Discolouration	1 2 3 4 5	No discolouration (0% of concrete surface discoloured) Slight discolouration (from 0 to 25%) Moderate discolouration (from 25 to 50%) Extensive discolouration (from 50 to 100%) Overall discolouration (100%)	The term "discolouration" was used to describe a certain pinkish cream stain on surfaces of concrete.
Comments	-	-	Note any local peculiarities, positions of load tests, cores or other samples. If necessary, suggest further testing procedures.

TABLE 2 Classification of crack frequency

Distance between adjacent cracks (mm)	Description
0 - 100	Very closely spaced
100 - 250	Closely spaced
250 - 500	Moderately spaced
500 - 1000	Widely spaced
> 1000	Very widely spaced

TABLE 3 Classification of crack widths

Width (mm)	Description
0	Closed
0 - 1	Narrow
1 - 5	Moderately wide
5 - 10	Wide
> 10	Very wide

TABLE 4 Matrix for converting classification of concrete members into a scoring system for the summation map of the main structural frame of the car park.

GROUP HEADINGS WITH CLASSES 1 - 5		MULTIPLICATION FACTOR	MAXIMUM POSSIBLE POINTS IN EACH GROUP
Degree of exposure		5	25
Degree of cracking		5	25
Workmanship		3	15
Exudation		1	5
Discolouration		1	5
OTHER GROUP HEADINGS		ADDITION FACTOR*	
Crack Description	Alkali-silica reactivity	5	10
	Reinforcement corrosion	5	
	Unrestrained drying shrinkage	3	
	Structural distress or Frost	3	
	Restrained drying shrinkage	2	
	Plastic shrinkage	1	
Concrete type **	Mix type A or C (reinforced concrete) 1	x2 if w/c = 1 - 2 x4 if w/c = 3 - 4	12
	Mix type B (mass concrete) 2	x6 if w/c = 5	
Structural function	Beam	3	3
	Column	3	
	Parapet wall	1	
	Retaining wall	1	
		TOTAL POSSIBLE MAXIMUM POINTS	100

Notes: *Where two crack types were extensive, then the addition factors of each were added together. Where three crack types were extensive, then the two with the highest addition factors were chosen and treated in the same manner as when only two crack types were extensive. Hence the maximum possible number of points in this group was when alkali-silica reactivity and reinforcement corrosion occurred within the same concrete pour (i.e. 5+5 = 10)

**Concrete mix types were determined by inspection of records and by visual observations of the structure.

whole structure coloured in accordance with its risk group (Table 5).

2.3. Detailed mapping of selected locations at the car park

2.3.1. Nine structural members were chosen for detailed field observation and testing. All were selected with particular reference to accessibility, exposure, structural function of the member, mix type, crack intensity and crack pattern. The following is a brief description of the systematic stages which were undertaken during the mapping of each member. The procedure follows that developed by Pollock et al. (1981)/3/:

(a) The first step was to mark an indelible reference grid in colour on the concrete surface.

(b) An indelible black line was then drawn alongside all cracks visible under an X10 hand lens. The end of each crack was indicated by drawing a short line at right angles to the line of the crack. Cracks which passed beyond mapped areas were shown by an arrow at their ends.

(c) Steel reinforcement was located using a cover meter and plotted on the concrete surface using lines of another colour.

(d) Areas of surface spalling, incipient spalling or hollowness were located and traced by sounding the concrete at close centres with a Schmidt Hammer.

(e) With reference to the grid, an accurate 1 : 10 scale drawing of the features listed above was prepared. Other significant surface features such as those described above were included on the drawing. Crack widths were determined by using an X10 magnifying glass with graticule. A reasonable diagnosis can be made from a drawing of the concrete member and this information can be extended to similar members showing signs of distress in other parts of a structure. An accurate drawing is also a permanent record of the state of the selected member at a particular moment in time.

(f) An overall colour photograph was taken with position, date and scale included.

(g) The finished drawing was studied to differentiate characteristic crack patterns and associated features. The interpretation helped to decide whether or not exploratory site testing and further examination was required. The relevant site tests have been summarised elsewhere /3/.

TABLE 5 Classification of risk of deterioration of the car park

Points (Table 4)	Risk of further deterioration
91 - 100	Extremely high
71 - 90	Very high
61 - 70	High
51 - 60	Moderate
41 - 50	Low
31 - 40	Very low
19 - 30	Extremely low

3. DISCUSSION OF THE CLASSIFICATION SYSTEM

3.1. During the classification survey several observations were made on the advantages and limitations of the system as follows:

(a) The classification provided a practical alternative to the use of purely written descriptions because it allowed the inspection to be conducted in a rapid and uniform manner, and the results used for analytical work.

(b) The reliability of the system depended upon the thoroughness and quality of the inspection, available records and the experience of the personnel responsible.

(c) It was important to develop a scheme which allowed agreement between independent workers; this scheme enabled different inspectors to agree generally to within half a point on any of the classification scores of 1 to 5.

(d) The classification was, however, somewhat subjective in that the assignment of a particular score depended on factors such as the weather, e.g. cracks were more visible on damp concrete than on dry concrete.

(e) Surveys of various other structures in south-west England suggested that comparative use of the classification is best when applied to structures made of similar materials existing in a similar environment, and constructed to a similar overall standard of workmanship.

(f) Great care is called for if the information is to be used for maintenance purposes or for estimation of the rates of deterioration, since it is sometimes easy to over-estimate a class (Table 1).

(g) Although the matrix in Table 4 helped to assess the importance of individual factors which might have contributed to deterioration, it is not universal for the following reasons:

(i) It accounted for only forms of deterioration observed in one particular structure at one moment in time. It would have to be modified for use in investigations of structues made of different materials in different environments and showing different defects.

(ii) Within one structure there were more types of structural elements than those suggested in Table 4. However, some were inseparable. For example, the two largest columns in the structure were more important than the remaining load-bearing members, yet it was impractical to incorporate this difference into the scheme. Fortunately in this case the results were not affected to a significant extent, for although the additional factors in Table 4 which correspond to apparently important structural function appear to be rather low, it seemed that the car park was strongly designed. Structural function would be a far more important factor in a weaker structure. Comprehensive in situ load tests had showed that the car park was structurally sound at the time of this investigation.

(iii) It cannot take full account of future variation in weather or exposure conditions, induced loads or of later extensions to the structure. However, the matrix could be altered accordingly depending upon which factors would be most important in the future.

(iv) For reasons including those noted above, future classification surveys of the car park should be carried out in a manner as similar as possible to this investigation in order to allow reasonable comparisons to be made.

4. RATES OF DETERIORATION

4.1. Litte published research on the rates of deterioration of concrete is available. However, nomographs have been developed for the determination of the rates of deterioration of reinforced concrete piles/1/. A simpler and perhaps more versatile and practical approach involved the application of observational techniques of a classification survey to the assessment of rates of deterioration of concrete structures in the Middle East/4/. Some 90 concrete structues were inspected, mapped and sampled and the results used to implement a trend line for rates of deterioration in mass and reinforced concrete structures in both marine and non-marine environments.

4.2. The present scheme follows that adopted in the Middle East in that the age of each structure at the time of observation was plotted against condition of the concrete/4/. The latter was measured by the degree of cracking in the classification scale of 1-5. It must be emphasised, though that the method is entirely empirical and based only on observational judgements. Furthermore, there are many factors which may affect rates of deterioration in different concretes and their interaction is complex. Therefore, results obtained from this type of survey must be treated with caution.

4.3. In order to help establish the rate of progress of the alkali-silica disease in particular structures, eight other concrete structures in the area were inspected, which were all suffering from the same type of deterioration. It was thought that they were all constructed using similar aggregate and cement to those used in the cast in situ concrete of the car park, and all existed in a broadly similar environment. It was necessary to study only these structures so that a reasonable correlation could be made between the condition of each of them and the condition of the car park. The factors common to all the structures enabled a trend envelope to be established by cancelling out some of the variables. Most of the structures, including the car park, were built in the late 1960's or early 1970's. As the age of the structures observed are somewhat similar any trend indicated by them must be considered very speculative. More structures of different ages having similar characteristics to the above need to be found (if present) in order to allow a more accurate rates prediction.

4.4. Figure 1 is the graphical plot of the average degree of cracking of each structure against age at time of observation. The average condition was determined by examining the structure and choosing a member considered to be representative of the total state of deterioration. Thus the average case was not necessarily the worst condition. A preliminary envelope for all points has been established, but does not pass through the origin. This was due to the fact that apparently none of the case histories showed signs of deterioration resulting from alkali-aggregate reactivity until several years had elapsed from the time of construction. This phenomenon appears typical of the local structures with alkali-silica reaction. It differs from the envelopes established for Middle East concrete structure showing mainly reinforcement corrosion and other problems associated with the salty, hot, humid weather conditions/4/. Those envelopes passed through the origin indicating that signs of deterioration became evident immediately after construction.

5. **SUMMARY AND CONCLUSIONS**

5.1. In the investigation of concrete structures in south-west England, emphasis was laid upon detailed description of the visible symptoms of deterioration. This type of investigation is not intended to replace analytical laboratory studies, but is intended to provide a basis for initial diagnosis and more detailed field and laboratory examination. The particular features of each individual structure involving various influencing factors must be studied before the relationship between effects and causes of deterioration can be established.

5.2. Detailed mapping and testing of selected locations provided evidence to help identify the cause or causes of cracking. This supplemented the classification study, which helped indicate the rate of deterioration. The production of a simple coloured summation map, based on the classification indicated areas at risk and aided the selection of areas which were in need of further study and/or maintenance and repair. It is clear that there is room for detailed surveys within concrete technology, and within the bounds of this study there is scope for improvement.

5.3. Leaching of calcium hydroxide, sometimes locally in large quantities, and the precipitation of calcium carbonate on surfaces were phenomena frequently recorded. This was considered to be a secondary effect and together with other signs and varying amounts of drying shrinkage cracking was in part indicative of wet original mixes. This type of cracking, together with the effects of reinforcement corrosion, frost attack, structural distress and plastic cracking were regarded as additional factors which had contributed in varying extents to a total picture of deterioration which was largely due to alkali-silica reactivity.

5.4. In the car park, expansion joints and deficiencies in the drainage system were allowing the concentration of alkalies by irregular uni-directional moisture flows, which locally increased the incidence and rates of the alkali-silica reaction. This demonstrates the need for appropriate design and regular maintenance checks.

5.5. Apart from variations in the proportion of reactive particles in the aggregate, the rate of alkali-silica reactive cracking is affected by degree of exposure, mix design and workmanship. Dry (low w/c ratio), strong well made concrete appears to crack at a slower rate than concrete with deficiencies and which allows the ingress of moisture.

5.6. The basic mapwork crack pattern due to alkali reactivity can be readily modified by existing cracks and stress fields in or imposed on the concrete. It is suggested that to a certain extent the disease is parasitic in that it extends early formed non progressive cracks and forms modified patterns of cracks with other progressive cracks, for example those imposed from reinforcement corrosion.

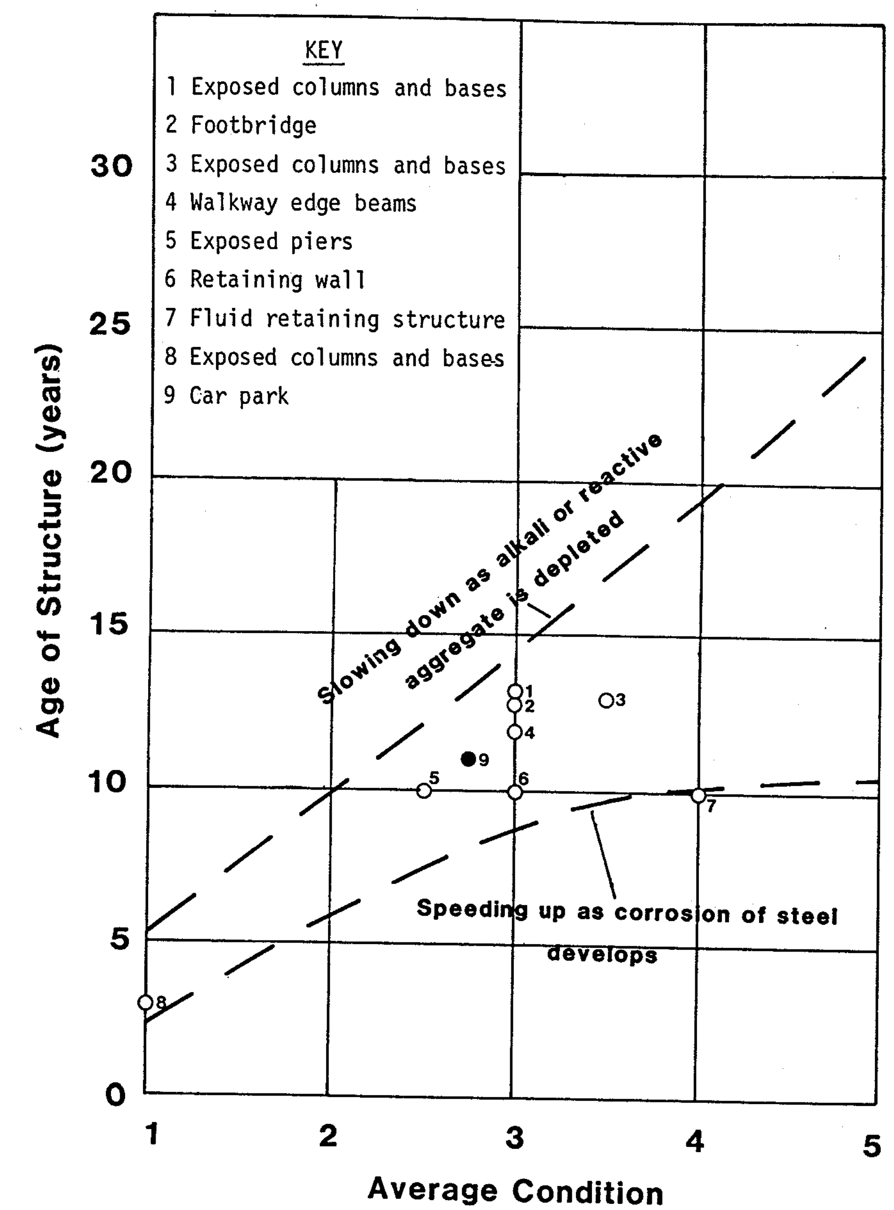

Figure 1. A speculative trend envelope of age v. average deterioration for nine concrete structures in south west England showing signs of distress due to alkali silica reactivity.

Note apparently higher rate for the fluid retaining structures.

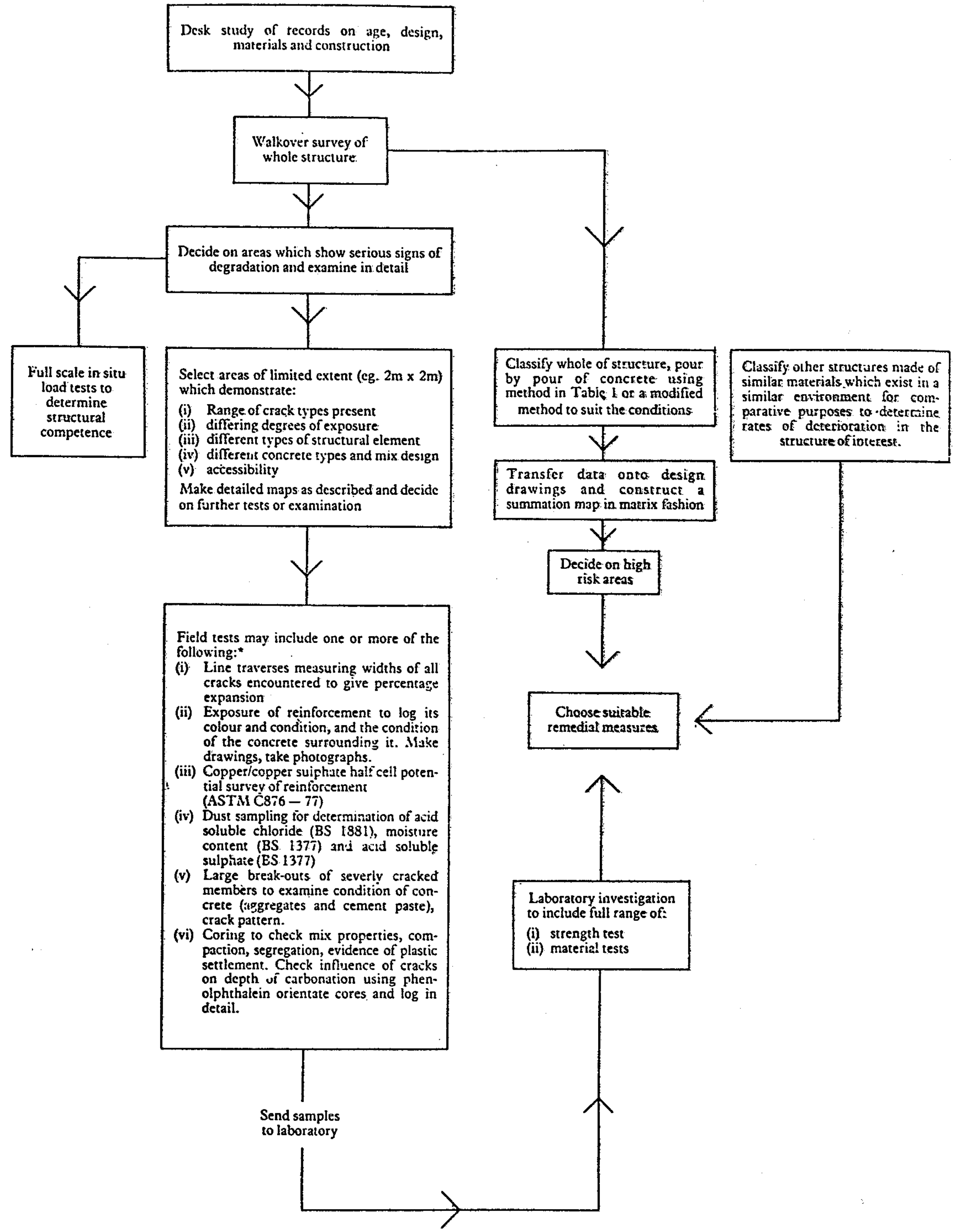

Figure 2. Flow chart to outline investigations of deteriorated concrete (in part after Pollock et al., 1981.)/3/.

*Blight et al. (1981) discuss the use of ultrasonic pulse velocities to determine the extent of cracking./7/.

5.7. Detailed inspections, of a type similar to that shown in Figure 2, ideally should be performed early on in the life of a structure to detect early isolated cases of rapid deterioration, particularly as more cases of alkali-aggregate reaction come to light in Britain Investigations repeated at regular intervals thereafter would provide information on the progression of deterioration and enable decisions to be made on appropriate remedial measures.

5.8. Consideration of items 4 to 7 coupled with observations made on all the structures inspected in south-west England leads to the conclusion that 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 by limiting passage of moisture across or through the concrete. Dense good quality concrete with minimal tendency to crack, for reasons other than alkalki reactivity, should be made to further avoid potential deterioration.

ACKNOWLEDGEMENTS

The authors wish to thank all members of the staff in the Department of Geological Sciences at Queen Mary College who helped during the course of the work, in particular Dr. Alan B. Poole, Mott, Hay & Anderson (Consulting Engineers) are gratefully acknowledged for their generous help and financial assistance and particularly P. Wickens who worked with the authors during various stages of the investigation. R. Hemming of the Plymouth City Engineers Department was of great help during the survey and Engineering Geology Ltd. helped to prepare the manuscript.

REFERENCES

1. IDORN, G.M. Durability of concrete structures in Denmark. Published Ph D thesis, Technical University of Denmark, Copenhagen, 1967

2. FOOKES, P.G. An introduction to the influence of natural aggregates in the performance and durability of concrete. Q.J.eng.Geol.London, Vol.13, No.4, pp 207-229

3. POLLOCK, D.J., KAY, E.A. & FOOKES, P.G. Crack mapping for investigation of Middle East concrete. Concrete, 1981, Vol.15, No.5, pp 12-19

4. FOOKES, P.G., POLLOCK, D.J. & KAY, E.A. Middle East Concrete (2) - Rates of deterioration. Concrete, 1981, Vol.15, No.9, pp 12-19

5. GUTT, W.H. & NIXON, P.J. Alkali aggregate reaction in concrete in the U.K. Concrete, 1979, Vol.13, No.5

6. PALMER, D. Alkali aggregate reaction in Great Britain - the present position. Concrete, 1981, Vol. 15, No.3, pp 24-27

7. BLIGHT, G.E., McIVER, J.R., SCHUTTE, W.K. & RIMMER, R. The effects of alkali aggregate reaction on reinforced concrete structures made with Witwatersrand quartzite aggregate. Proc.Alkali-aggregate Conf., Cape Town, 1981.