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THE RESIDUAL SERVICE LIFE OF REINFORCED CONCRETE STRUCTURES

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ABSTRACT

This Report briefly describes the nature and scope of the work undertaken in BRITE-EURAM Project 4062, 'The residual service life of reinforced concrete structures'. The deterioration mechanisms considered were: alkali-silica reaction; freeze-thaw; corrosion.

The most significant output was a Users Manual in 4 Parts. The approach and philosophy adopted in drafting the Manual is described. This is followed by the presentation of a brief selection of the results of the extensive scientific research programme, with the emphasis on showing how these results have been assessed and transformed for use in the practical engineering assessment framework within the Users Manual.

The project has demonstrated the viability of producing a Users Manual which is engineering-based, while integrating the best-available scientific data. The Manual now needs to be developed further, by calibration in a series of controlled case studies.

INTRODUCTION

Much of the European infrastructure, built with modem materials, is now aging. Society's requirements, in performance/functional terms, is also changing, e.g. wider or stronger bridges to carry increasing volumes of traffic, or buildings in which quite different functions are performed compared with 30-40 years ago. Many structures are suffering deterioration due to aggressive actions, either not foreseen or inadequately treated at the initial design stage, e.g. the increased use of de-icing salts on roads leading to the corrosion of reinforcement in highway structures built in concrete.

For environmental and economic reasons, the trend is to manage maintain and upgrade existing structures, rather than to build new ones; approximately 40% of the output of the construction industry is now on maintenance and upgrading - and rising. To take rational decisions, in minimizing whole life costs compatible with perceived future changes in use, owners require reliable information on the technical performance of their structures, as affected by deterioration - both in terms of current state and predicted future decay. Generally, for each structure, this requires an assessment, preceded by investigation and diagnosis.

At present, the methodology of investigation is evolving reasonably well - driven by increased need - with the development of more sophisticated measurement techniques. The interpretation of data from such investigations still remains a problem, especially in pure structural terms (strength, stiffness, stability and serviceability). Judgments are made on a 1 -off ad hoc basis, and there is evidence that these judgments are not always right, simply because a general overall framework, backed by appropriate technology, is not yet properly in place. We have a few unexpected failures; more commonly, conservative judgments are made, to take remedial action perhaps before it is really necessary. This lack of precision costs millions of ecu annually.

In parallel to this changing scene in practice, much research work has been done on the science of deterioration. Mostly, this is laboratory-based, in the quest for understanding and the development of hypotheses to explain observed phenomena. Some experimental work has been done on outdoor exposure sites, but this is still essentiality research. Very many structures have now been investigated, but on an individual basis, and there is a lack of general cohesion and consensus on the results obtained.

There is therefore an urgent need to bridge the gap between the scientific arena and the practical needs of assessment in the field. This was a major objective in BRITE 4062. Scientific research was done to study additional variables, and to confirm understanding and the basis of the predictive models to be developed. However, the main thrust of this aspect of the Project has been to 'translate' the best available science into a format suitable for engineering assessment - quite a difficult task.

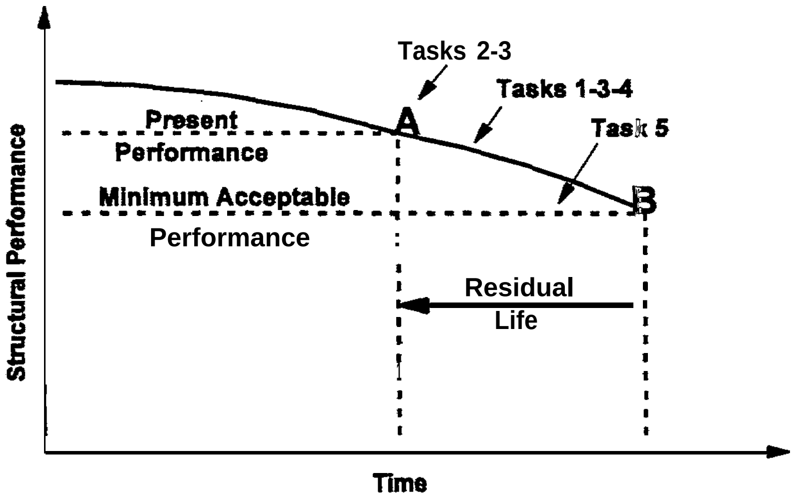
An outline framework for structural assessment has also been produced, as part of the Project. Here, it has been recognised that assessment will never be an exact science. While many of the factors involved are stochastic in nature - indicative of a full probabilistic approach to assessment - practical reality, and the real needs of owners (which were established by consultation during the Project), suggests a deterministic approach, more in line with the semi-probabilistic approach, familiar to all designers and the basis of most Codes of Practice. This has the added advantage of simplicity, with the potential of widespread use in practice, while permitting comparisons with original designs.

A basic task in BRITE 4062 was to confirm the validity of such an approach to assessment, and, if positive, to put forward a proposal for the necessary framework. This has been done, in the form of a 4-Part Users Manual - the key Deliverable from the Project. In this synthesis of the work, the emphasis will be on the evolution of the Users Manual, while briefly indicating the scope of the Project as a whole.

SCOPE OF BRITE 4062

3 deterioration mechanisms are treated: alkali-silica reaction; freeze-thaw; corrosion. A simple sketch of assessment where deterioration is involved is shown in Figure 1. The associated task matrix, within BRITE 4062, is shown in Table 1.

Much of the work was of the scientific experimental type, aimed at an understanding of the variables involved in Tasks 1, 3 and 4. This was complemented by structural testing, for all 3 mechanisms but especially for corrosion.



Figure'1: Schematic illustration of assumed behaviour

Table 1: Task Matrix

TASKS	SUBTASKS		
	Corrosion of Reinforcement	**Freeze/thaw damage**	**Alkali-Silica reaction**
1 Define aggressivity of environment	1.1	1.2	1.3
2 Assess current state materials in member	2.1	2.2	2.3
3 Define structural performance from material states	3.1,3.2, 3.3 & 3.4	3.5	3.6
4 Assess deterioration rates	4.1	4.2	4.3
5 Define minimum acceptable performance			
6 Practical implementation [+ suggestion of remedial strategy]			

In terms of scientific research, the following variables were studied experimentally:-

Alkali-silica reaction -
- wetting and drying
- temperature
- exposure to salt
- free v. restrained expansion
- bond

Freeze-thaw damage	outer v. inner micro-climate types of frost attack critical degree of saturation number and intensity of freezing cycles exposure to salt bond critical spacing factor air content in the concrete
Corrosion	relative humidity concrete quality concrete cover temperature type of binder use of additives climatic and moisture conditions (including cyclic) corrosion v. cracking bond strength of beams and columns

For all mechanisms, the emphasis was on tasks 1-4 (Table 1) and in particular, on

defining the critical environmental conditions;

establishing and confirming methods of measurement for the current state of materials;

understanding the deterioration processes, and developing models capable of predicting the range of criteria established in Task 5, for minimum acceptable performance;

carrying out strength tests to confirm and calibrate the predictive models;

completing a range of experimental studies to investigate cases where. deterioration could have a unique influence on structural performance; examples are:-

(i) bond strength, for all 3 deterioration mechanisms
(ii) the relation between corrosion, cracking and spalling.

For the duration of the Project, all work was focussed on the completion of Task 6 (Table 1), which gradually evolved into a decision to attempt the production of a Users Manual. The results obtained were much influenced by this decision. Before presenting a sample of these results, it is useful to consider the actions and thought processes which conditioned the format of the Users Manual - and guided the entire work programme.

THE PROPOSED USERS MANUAL IN OUTLINE

Basic essentials

A Users Manual must be practical, and meet the real needs of owners and assessors. It is useful to begin at the end, and ask what information an owner may want at the end of an assessment.

Essentially, he will want to know if his structure is safe and serviceable now, and when it might become unsafe: associated with that are some possible future actions, as given in Table 2. An assessment should answer these questions.

Table 2: Possible future actions after assessment and factors involved.

ACTIONS

1.	Do nothing; inspect again in x years		
2.	No action now, but monitor		
3.	Routine maintenance; cosmetics; some patch repairs	]	evaluate cost/
4.	Remedial action: specialist repairs and/or protection	]	benefit in whole
5.	Partially replace, or upgrade, or strengthen	]	life costing
6.	Demolish and rebuild	]	terms

TIMESCALE	**FACTORS**
Now	Results from assessment
1-5 years	Future change in fiction
5-10 years	Future change in standards
10-25 years	Type and nature of structure
Longer term	Risk and consequences of failure

In addition, before writing a Users Manual, it is helpful to know which topics cause most concern for owners. At a workshop for Spanish, Swedish and UK owners in London in April 1995, the partnership asked some questions, and the feedback obtained is shown in Table 3: this indicates where most detail is needed.

Table 3: Feedback from owners of structures on topics where guidance in most needed

Item N“	Subject area	Score (%)	Ranking
1	Definition of environment	69.4	8
2	Identification of causes of damage: sampling	78.3	4
3	Evaluation of test methods	68.8	9
4	Interpretation of data from tests	80.5	3
5	Identification of sensitive structures& details	71.1	6=
6	Definition of minimum technical performance	86.1	2
7	Levels of overall safety& serviceability	87.2	1
8	Calculation/Analytical methods	71,1	6=
9	Reliability of alternative repair methods	76.1	5

As a perspective, it is also helpful - whether in preparing a Users' Manual or conducting an actual assessment - to consider what the effects of deterioration might be, in structurally significant terms. Very simply, deterioration can cause:-

(i)	Loss of section	e.g.	concrete spalling corrosion of reinforcement (general or local)
(ii)	Reduction in mechanical properties	e.g.	in the strength of materials or in the stiffness of elements

(iii) Excessive deformation (local or overall), thus inducing alternative modes of behaviour or rupture of critical sections

These effects are most significant when considering safety, but are also relevant in serviceability terms. It follows that:-

(a) Data obtained from the investigative part of the assessment must be able to be interpreted in those terms;

(b) Any modelling, involved in the analyses of the structure as a whole, or in the calculation of the strength of critical sections, must be capable of receiving data covering items (i)-(iii) above, and producing realistic estimates of strength, stiffness and serviceability, due to the deterioration.

Assessment procedure

The flow chart assessment, derived form Project 4062, is shown in Figure 2, as far as preliminary assessment (ISSR rating). Assessment is seen as progressive, and the first ISSR stage is in fact a form of damage classification. What is clearly seen from Figure 2 is the need to consider both structural and deterioration issues from the beginning. Structural issues are important for the analyses stage in arriving at an ISSR rating; they became even more important should the ISSR rating be unsatisfactory, leading to the need for a more detailed assessment of the effects of deterioration on individual action effects (e.g. bending, shear, bond, etc.).

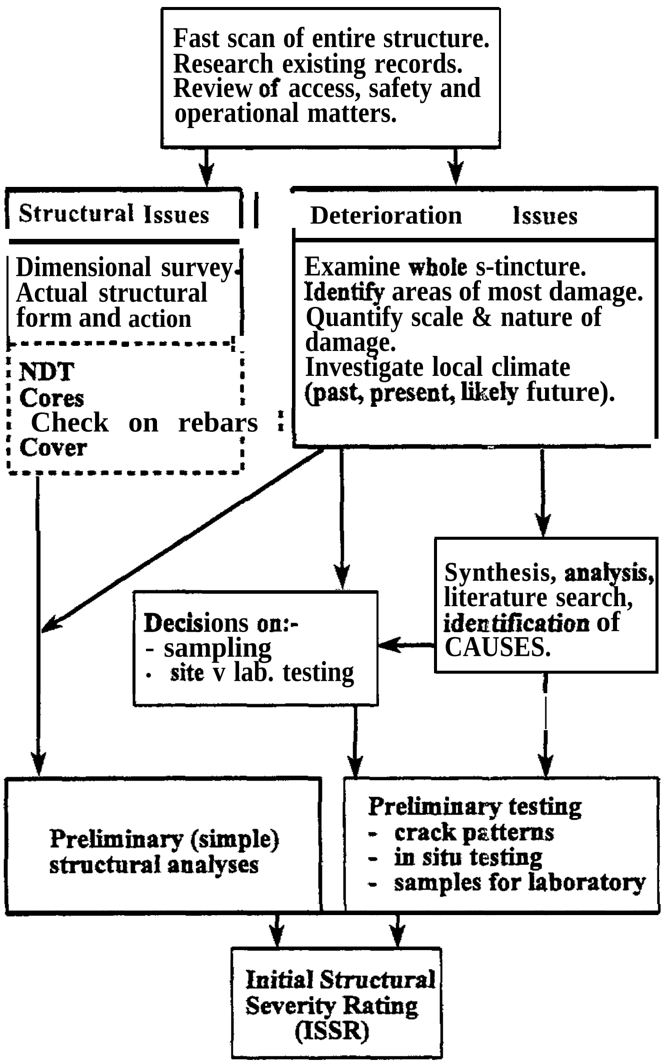


Figure 2: Possible provisional plan, in progressing towards a preliminary assessment

Minimum technical performance (Figure 1)

It is important to have some idea of what is acceptable to the owner, in terms of minimum performance - with respect to physical deterioration, in the first instance, The reasons are these:-

(a) The effect that this has on the nature and scale of the investigative work.
(b) The influence on the development of predictive models.
(c) The input into the recommended future structural management strategy (Table 2).

Possible minimum performance criteria for corrosion are shown in Table 4 as an example; the Notes to this Table are important, both in practice, and in terms of directing the research within BRITE 4062.

Table 4: Possible minimum performance criteria - corrosion

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1. Carbonation or chloride front has reached the reinforcement.
2. Corrosion has just started, i.e. 1. above, and availability of O_2, H_20 + critical threshold level (for Cl–).
3. Corrosion has caused cracking parallel to the bar, and the crack width is equal to χmm.
4. Corrosion has removed y?! of the cross section from z% of the reinforcement.

__Notes__

(a) A knowledge of maximum likely corrosion rate is always necessary.

(b) The ability to predict each criterion is essential. The ability to predict the time from one criterion to the next is also essential.

Clearly, values for corrosion rates have to be established, relative to a range of possible environmental conditions on site. Equally clear is the fact that the predictive models to be developed from the Project must be able to predict the full range of limiting criteria which owners may wish to use, Minimum performance criteria, in this sense, will vary from structure to structure and from owner to owner.

Strength, safety and reliability

Engineers are used to the traditional design condition for the ultimate limit state:-

$$S_d \leq R_d$$

An important question is how should this be transferred to assessment. There is no single or easy answer. Many of the variables involved in deterioration are stochastic, and some owners may be attracted to a full reliability assessment. For normal *use*, the BRITE 4062 partnership has taken the view that owners may want to compare assessed strength with that of the original design. This leads to a deterministic approach based on the semi-probabilistic methods in most design codes, e.g. Eurocode 2, based on the principlesin1S02394 and derived from the work of CEB.

In this context, there are perhaps three matters to be considered:-

1. A re-analysis of the structure, using measured values for areas and stiffnesses (as modified by deterioration) to establish how the distribution of moments and forces may have changed, due to the effects of deterioration. This should always be the approach, unless there is reason to believe that the deterioration (either in nature or scale) invalidates the basic assumptions of traditional analysis (see 3. below).

2. A check on the strength of critical sections, in terms of their ability to resist the (new) maximum values for bending, shear etc. BRITE 4062 believes that this can be done by modifying the traditional design equations.

3. A careful evaluation of the structure, to detect possible non-traditional modes of behaviour and failure caused uniquely by the deterioration (e.g. global or local buckling, anchorage or bond failure).

In all three cases, the question of what values to use for partial safety factors arises. There is no unique answer, since the level of knowledge will vary between structures, even if that knowledge is greater than for initial design, as indicated in Table 5. This Table implies that lower values for partial factors maybe used for the same reliability. In Part 1 of the Users Manual, an attempt is made, using the principles of ISO 2394, to break down the safety factors in Eurocode 2 into their component parts, and to make recommendations for values to be used in assessment work.

In turn, this leads to the **type** of progressive assessment outlined in Table 6. Preliminary assessment corresponds to the ISSR stage in Figure 2; the adequacy of the ISSR rating could be judged simply, as indicated under the 'Result' heading in the Table. Above all, this Table attempts to answer some of the action questions in Table 2, while confirming the opinion expressed earlier that assessment will never be an exact science - and most probably unique to each structure.

Table 5: Design v Assessment: Significant Differences

Item	Design	Assessment
Material properties	Assumed	Measured
Dead loads	Calculated	Accurately determined
Live loads	Assumed	Assessed
Analysis	Code based	More rigorous alternatives
Load effects	Bending, shear, compression, cracking dominate	Anchorage, bond, detailing may be more important
Environment	Assumed classification	Definition of macro- and micro-climate
Reliability	Code values for safety factors	Smaller factors (?) for same reliability

Table 6: Schematic outline of progressive assessment procedures

Assessment Phase	Conclusion			Recommendations
	Based on	Result	Reason	
preliminary	Records Survey data Site Measurement Cores Crack pattern & widths Simple analyses	Adequate	Sufficient residual service life and load-carrying capacity.	Monitor
		Borderline	Insufficient data; or residual service life and load-carrying capacity marginally less than that required.	Detailed assessment
		Inadequate	Insufficient residual service life and load-carrying capacity.	Modify adequacy criteria, and reassess, Consider alternative remedial actions. Detailed assessment,
Detailed	As preliminary plus: Monitoring Laboratory tests More sophisticated analyses	Adequate	Sufficient capacity for required loading (by calculation or load test).	Monitor
		Borderline	Insufficient data; or residual service life and load-carrying capacity marginally less than that required.	Load test to classify as adequate or inadequate. Consider future management and maintenance.
		Inadequate	Insufficient residual service life and load-carrying capacity (by calculation or load test).	Options are: Modify adequacy criteria and/or evaluate actual loading, and reassess. Consider possible actions in Table 2.

Contents of the Users Manual

The Manual is in 4 PARTS, as follows:-

PART 1: General approach and procedures
PART 2: ASR - Preliminary and detailed assessment
PART 3: Frost action - Preliminary and detailed assessment
PART 4: Corrosion - Preliminary and detailed assessment

The contents list of Part 1 of the Manual is given in Table 7.

Table 7: Contents list of PART 1 of the USERS MANUAL

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1. **INTRODUCTION**
2. **OBJECTIVES OF ASSESSMENT**
3. **OVERALL APPROACH**
4. **THE PRELIMINARY PLAN**
   - (a) General
   - (b) sampling
   - (c) Records, logging data, etc.
5. **STRUCTURAL SURVEY**
   - (a) General
   - (b) Structural issues
   - (c) Identification and classification of defects
   - (d) Further (progressive) testing
   - (e) Interpretation of data
   - (f) Synergetic effects
6. **PRELIMINARY STRUCTURAL ASSESSMENT**
7. **MINIMUM TECHNICAL PERFORMANCE**
8. **DETAILED STRUCTURAL ASSESSMENT**
   - (a) Introduction
   - (b) The basic approach to calculating the resistance of elements
   - (c) Factors to be taken into account
   - (d) Choice of safety factors in assessment
   - (e) Methods of analysis
9. **REFERENCES**

Parts 2-4 all have the same major chapter headings as follows:-

- Introduction
- Pre-assessment (diagnosis, current state and prediction)
- Preliminary assessment
- Detailed assessment
- Structural management strategy

It will be clear from this brief review that the draft Users Manual has been written from the viewpoint of an owner or assessor, to identify the necessary actions and methodology, and to give as much practical guidance as possible - especially on diagnosis, prediction and the engineering interpretation of data. It is not a technical publication containing scientific reporting of research. It is a practical framework for assessment, both pragmatic and flexible, which permits engineering judgement in individual cases. Within that framework, the BRITE 4062 partnership has attempted to express the scientific data from its experimental programme in a format which permits optimum judgments to be made. In the 'Results' section of this Report, some indication is given of how that has been done.

RESULTS

Introduction

Detailed results are contained in 28 deliverables, 25 published papers and in the Users Manual itself. What follows in this section is only a very brief selection, with the emphasis on illustrating how the scientific data obtained has been 'translated', for use in the Manual outlined earlier.

Aggressivity of the environment

Activities in this area can be summarise under three broad headings:-

1. How to establish and classify the critical local external environment for each deterioration mechanisms, in a way which is representative of real (variable) conditions on site.

2. The prediction of the inner environment within the concrete from known external micro-climates.

3. The influence of different aggressive environments (type and intensity) on concretes having variable constituents, qualities and properties.

A significant factor in this area is the moisture condition within the concrete, and this is the only aspect of the extensive work done in this area to be illustrated here. Figure 3 shows a typical calculation of moisture condition from a known (controlled) external micro-climate, and for 2 qualities of concrete. The computer program, developed from the freeze-thaw part of BRITE 4062, to make these predictions was calibrated against a wide range of micro-climates and concrete qualities. Moisture. state is important for all 3 deterioration mechanisms, and therefore this technique has wide application.

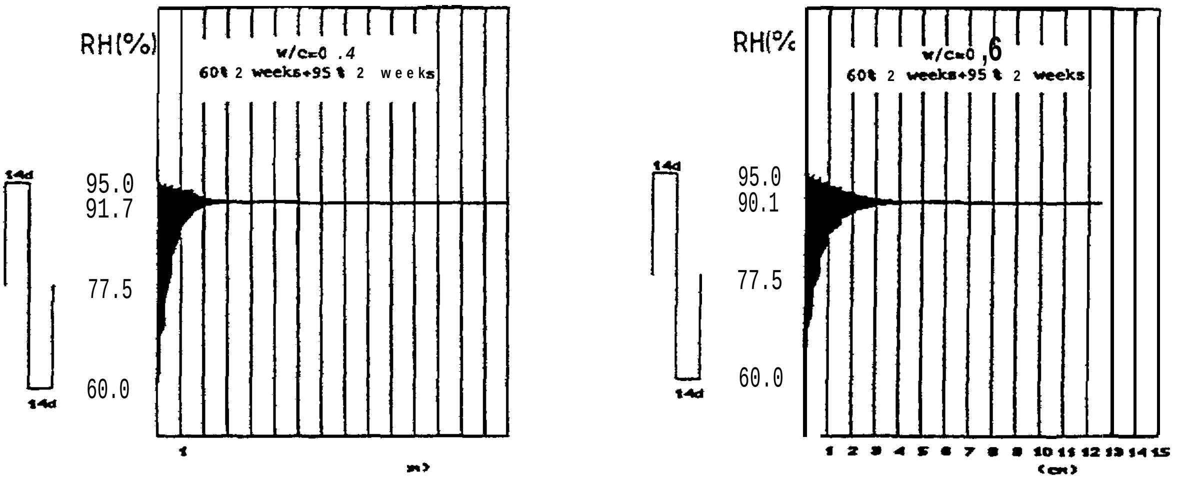

Figure 3: Examples of calculated moisture variations in the surface part of concrete exposed to an RH-variation between 60% and 95°/0. Left: w/c=0,40. Right: w/c-ratio 0.60.

Alkali-aggregate reaction

The aspect of work on this sub-task, which is illustrated here, relates to the structural significance of the reaction. Expansion due to the reaction is a key factor. Earlier attempts at an Initial Structural Severity Rating (ISSR) - see Figure 2- have been based on free expansion. In general, a concrete with a large free expansion is more at risk. However, in a real structure, the existence of restraints can significantly reduce the expansion,

A major contribution from BRITE 4062 has been the establishment of a relationship between free and restrained expansion, and hence to propose a new Severity Rating. This is shown in Table 8.

Table 8: **Structure element severity rating -in terms of restrained expansion, due to ASR**

Reinforcement detailing class	Restrained Expansion (mm/m)							
	< 1		1 to 2		2 t0 3		>3	
	Consequences of Failure							
	slight	sig	slight	sig	slight	sig	slight	sig
All	n	n	D	C	C	B	B	A

n = Negligible D = Mild C = Moderate B = Severe A = **Very** Severe

By relating expansion to the key mechanical properties, via experimental work, information of the type shown in Table 9 can be produced, if a detailed calculation of the strength of elements is considered necessary. This in turn means that the investigative part of an assessment can be concentrated on obtaining a realistic value for restrained expansion.

Table 9: Lower bound residual uniaxial compressive strengths

Restrained expansion (mm/m)	Percentage of residual strength
0.5	95
1.0	80
2.5	60
5.0	60
10.0	

Freeze-thaw damage

The work done on freeze-thaw action within BRITE 4062 was extremely comprehensive and cohesive, in the sense that all the tasks in Table 1 were very much inter-related in practice. Both scientific and engineering experimental work was undertaken, but the major contributions have been to synthesise all available information, to develop a good basic understanding, and to produce predictive models which reflect that understanding.

It is therefore more difficult to select one particular aspect of the work, which illustrates the whole picture. However, since, as for all mechanisms, an attempt was again made to use scientific measurements for engineering assessment, the issue of scaling in the presence of salts is briefly illustrated. Figure 4 shows typical experimental data for different salt concentrations and a particular minimum freezing temperature. Figure 5 shows schematically the approach to modelling future scaling as possibly affected by external effects.

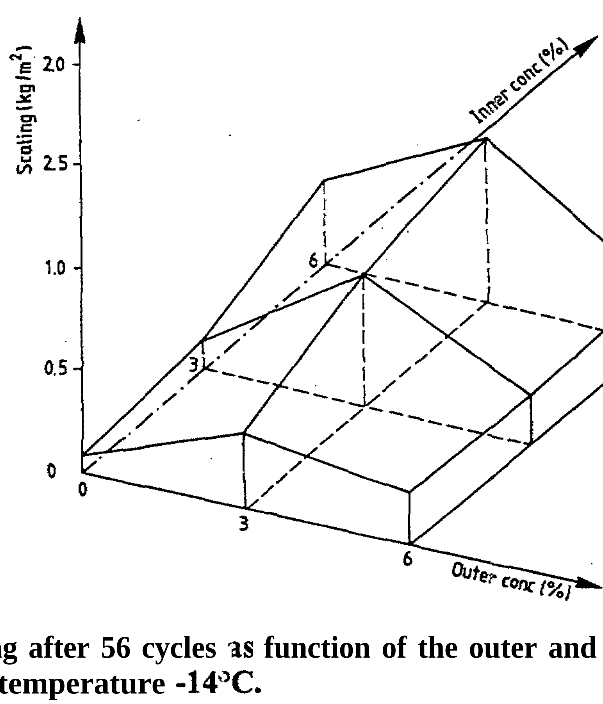

Figure 4: Salt scaling after 56 cycles as function of the outer and inner salt concentrations. Minimum freezing temperature -14°C.

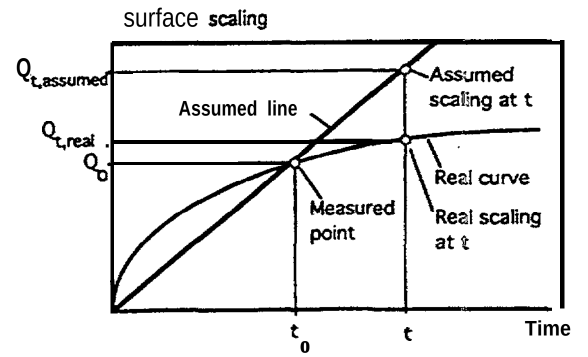

Figure 5: Linear extrapolation of retarded salt scaling. The retardation being caused by inhomogeneties in the surface part of the concrete.

Corrosion

Corrosion is the deterioration mechanisms where probably least was known about the structural effects at the start of BRITE 4062. In engineering terms, the possible effects were quickly identified as shown in Figure 6. In simple terms, the task was to quantify these, before then considering the consequences directly, in terms of reduced structural capacity.

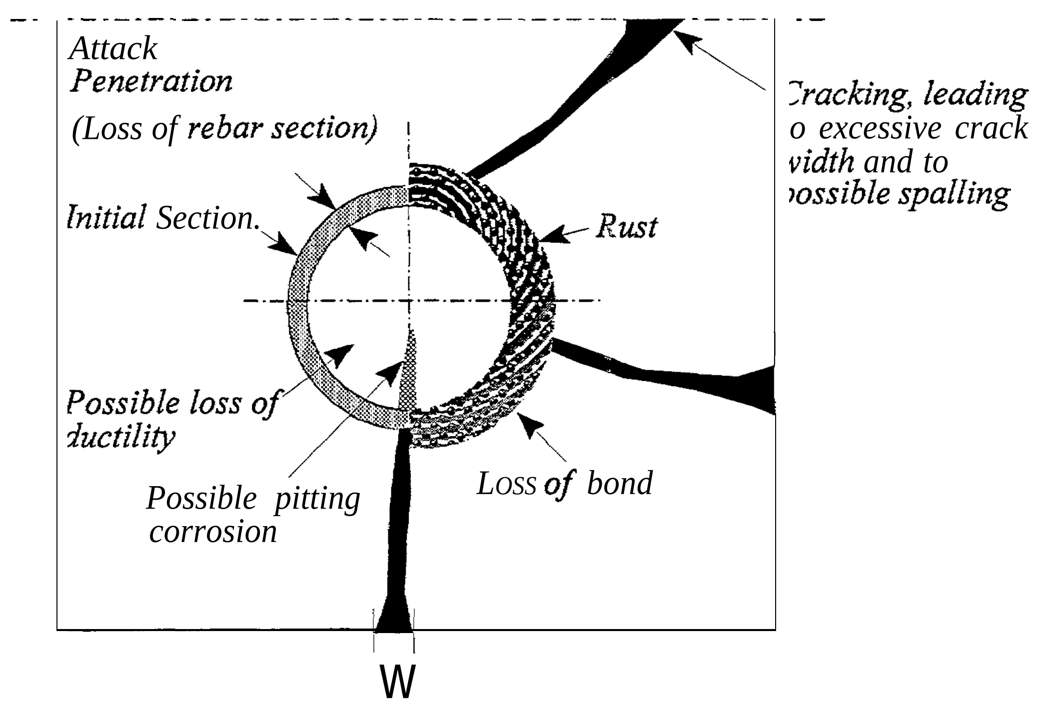

Figure 6: Schematic representation of the effects of corrosion

A cameo of how this was done is given in Figures 7-10. Firstly, in Figure 7, there is the gathering of data, mostly in the laboratory; this helps identify the relative importance of a large number of variables. Next, the laboratory data are related to site measurements - for example, Figure 8 which shows a cumulative frequency for corrosion rate. In this case, this was most important, since, under even the most severe conditions, corrosion rates on site are significantly less than those from the laboratory.

The next stage is to convert this information into general guidance on expected corrosion rate in different micro-climates; this is shown typically in Figure 9.

Moving on to the structural influence, when the corrosion rate is known, typically we have Figure 10, which shows the loss of cross-section area for 2 bar sizes, as affected by uniform or pitting corrosion. Using conventional design formulae, and taking account of any loss of concrete section or mechanical property, it is a simple matter to calculate residual strength after any period of time. This, in turn, can be checked against the minimum performance acceptable to the owner, and hence decisions taken as to when remedial action is necessary,

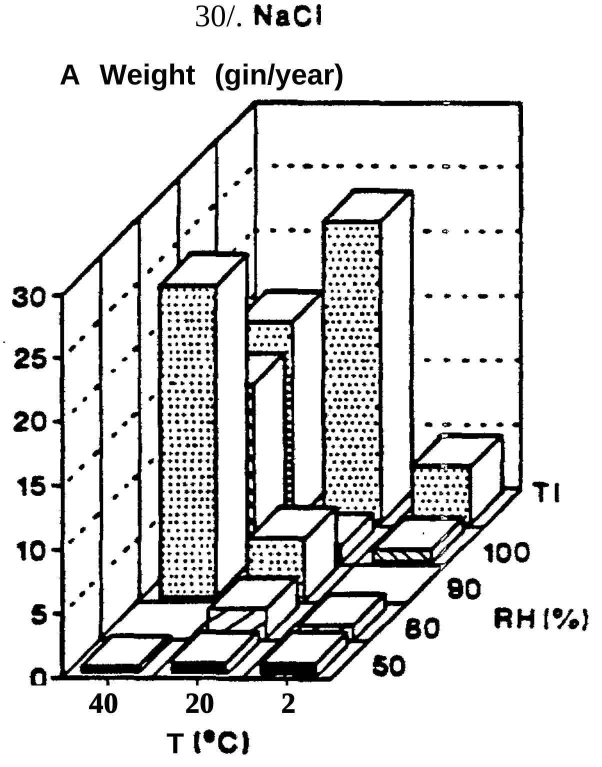

Figure 7: Corrosion rates, expressed in loss of rebar section (laboratory results)

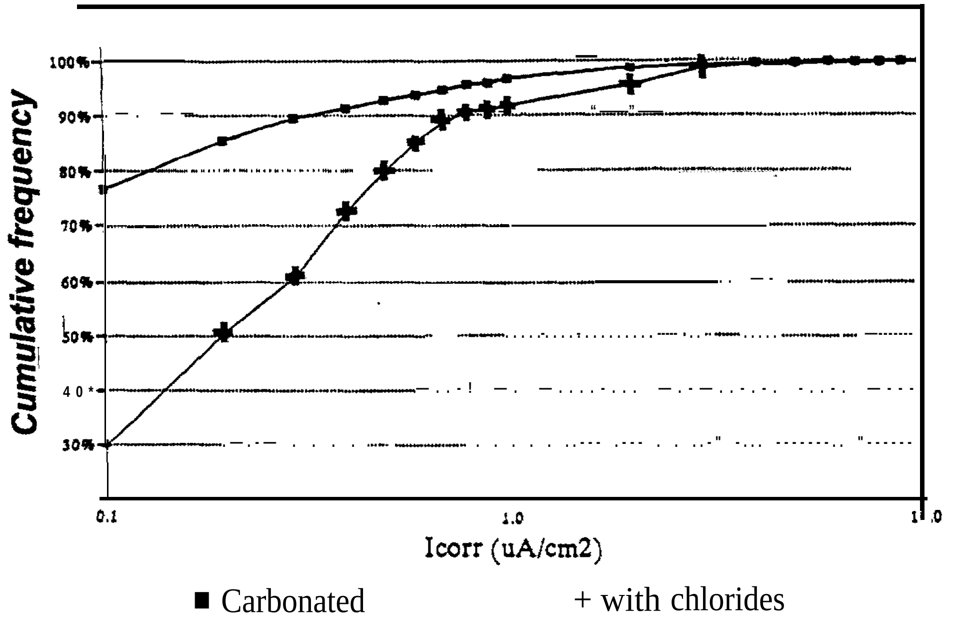

Figure 8: Cumulative frequency of I_{corr} values measured on site

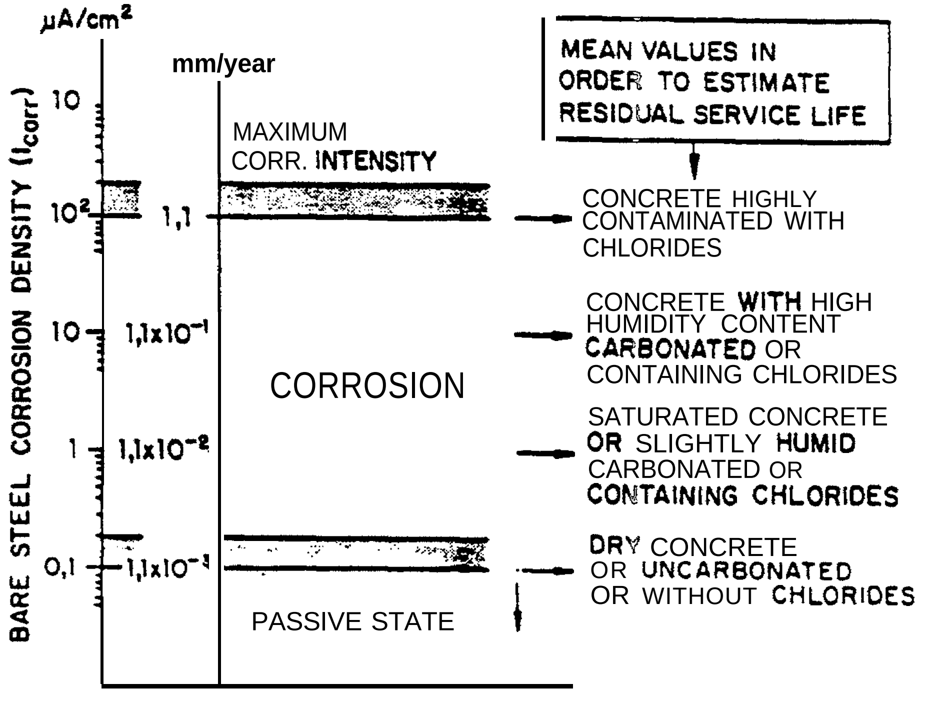

Figure 9: Corrosion rates, related to possible site environmental conditions

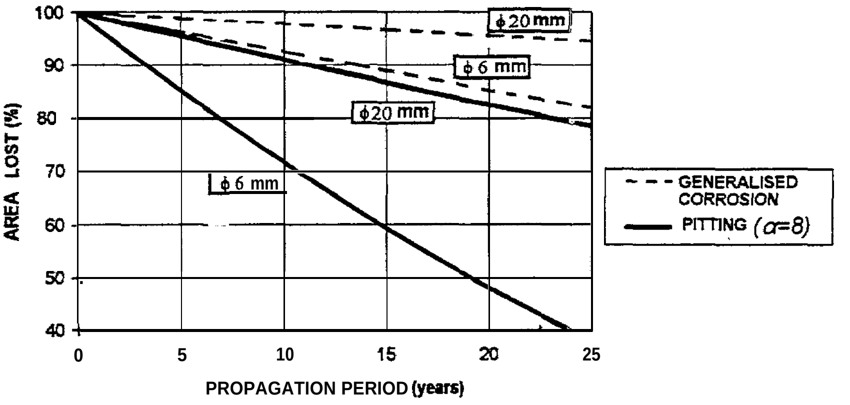

Figure 10: Decrease of bar sectional area for $I_{corr} = 1\ \mu A/cm^2$

This breathless description has been given to typify the approach in BRITE 4062, in producing information for the Users Manual. It represents only a small proportion of the variables and the results obtained.

Tasks 5 **and 6**

In effect, these two Tasks have been covered briefly in the earlier Section of this Report which dealt with the Users Manual. Space does not permit more information to be given.

CONCLUDING REMARKS

Detailed conclusions of a technical nature are impossible, because of the scope of the Project; this risks repeating much of the earlier detail. As a general conclusion, the Project was completed very successfully. All objectives were achieved.

A major conclusion is that the Project has demonstrated the viability of producing a practical Users Manual for the assessment of reinforced concrete structures. Assessment is still a relatively new technology, lacking an overall framework, in parallel to that which exists for initial design. Assessment will be much more significant in the future throughout Europe, as we learn to manage the existing infrastructure, in a climate of increasing environmental concern. A practical general framework and approach is therefore badly needed. The output from BRITE 4062 represents significant progress in that direction.

Of special significance is the User Manual, which has been produced in draft form; For the first time, science and engineering have been integrated in a practical way. It is strongly recommended that this Manual be developed further, and calibrated against a series of case studies, as recommended in the Exploitation Plan.

ACKNOWLEDGEMENTS

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