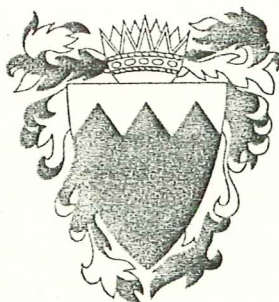
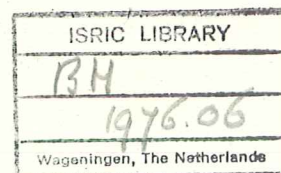


STATE OF BAHRAIN
Ministry of Works, Power and Water



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BAHRAIN SURFACE MATERIALS RESOURCES SURVEY

Volume V

**Hazards Associated with Salt Weathering
in Bahrain (Geomorphology 2)**

February 1976

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BAHRAIN SURFACE MATERIALS RESOURCES SURVEY

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+ Indicates participant only in first period of fieldwork (Dec. 1974).

* Indicates participant only in second period of fieldwork (April 1975).

All other team members participated in both periods of fieldwork.

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A CAUTIONARY NOTE

Every effort has been made to record both fully and accurately those significant aspects of the geomorphology, geology and pedology of Bahrain which were observed by the survey team and which have a bearing on its surface materials resources.

Nevertheless, for the reasons stated in the body of this report, there may remain errors of omission which necessitate that this report and the accompanying maps must be treated as work carried out at a reconnaissance level. In particular all the maps must be used with the understanding that they indicate relative locations and relationships rather than the exact dimensions of features and deposits.

For the most part the scientific terms used are defined in the text and appendices. In many instances this report follows the recommendations in The Preparation of Maps and Plans in terms of Engineering Geology (Quart. Jl. Eng. Geol. 5(4), 1972). However, as the members of the team are in the main neither engineers nor engineering geologists by profession, and some of the evaluations therefore may not be in precise engineering (soils and rock) terms, and must not be construed to be such.

This report presents the results of a feasibility study. It is not a site investigation. The data only provides a guide for future site investigations. The pit descriptions that accompany this report are those of geologists, geomorphologists and pedologists working in the field. They are therefore subjective and should not be taken as precise engineering descriptions.

All laboratory results are valid only within the constraints and limitations imposed by the tests employed.

The Universities who employ the survey members are in no way responsible for any element of this report.

V HAZARDS ASSOCIATED WITH SALT WEATHERING IN BAHRAIN

V.1 INTRODUCTION

Several natural hazards of engineering significance occur in Bahrain, and one to which the Survey devoted special attention is that of salt-weathering. This hazard is met in two significant ways. In the first instance the salt-weathering of materials used in the construction industry renders some less suitable than others for construction purposes. Secondly, the foundations of buildings and other structures in Bahrain (as in some other hot arid lands of the world) are known to be susceptible to attack by saline ground-waters. It is to these two problems that the Survey paid special attention since they are of such importance. In particular the team concentrated on the spatial aspects, the regional variations across Bahrain, of this hazard. The salt-weathering hazard is very complex in its behaviour (see Fookes and Collis, 1975). This Report draws attention to the information gathered by the Survey and which should be taken into account both in the management (planning) of Bahrain and in future systematic studies of the hazard itself.

Since an understanding of the salt-weathering hazard is of pressing urgency in the development of Bahrain it is described in Section V.2 before the results obtained by the Survey are presented. It is nevertheless important to emphasise that this is a very complex area of study which demands much greater study than was possible during the time available to the Survey team.

V.2 SALT WEATHERING HAZARD

1. Introduction to the Hazard

The presence of saline solutions and salts in materials used by the construction industry and in buildings, roads and other engineering structures in hot arid areas can create problems. The more serious of these include:

1. Alteration of the chemical composition of materials, which can lead to reduction in their strength and durability, or can promote volume changes that exercise a disruptive effect. For example, concrete can be chemically

altered in the presence of salts. One illustration is the reaction of free CaO in concrete with sulphates dissolved in water to form ettringite (calcium aluminium sulphate) which can lead to the disintegration of the concrete. Similarly, the corrosion of steel reinforcing bars in concrete in the presence of salts can cause an increase in the volume of the rods which exerts pressure on the surrounding concrete and may lead to its disintegration.

2. Salts and saline solutions in buildings and other structures may themselves undergo changes that can lead to the weakening or disintegration of the host materials. These changes may include:

- (a) the thermal expansion of the crystallised salts;
- (b) hydration of salts; and
- (c) the growth of salt crystals from solution.

All of these changes involve increases in the volume of salts, and under appropriate conditions such increases may exert pressure on the host materials. Removal of salts in solution from foundation fills for instance, can cause reductions in the volume of solid materials with serious consequences of increasing void space and subsequent settlement. Salts that may be responsible for these problems fall into one of three main categories:

- 1. Salts present in materials before its incorporation in buildings, roads etc. (e.g. salts emplaced during the deposition of sedimentary rocks; salts deposited in rocks from sea spray, rainfall, or ground-water; or salts formed during the manufacture of tiles, etc.);
- 2. Salts formed in structures as a result of chemical changes to the original materials;
- 3. Salts emplaced in buildings, roads etc. from external sources, of which the most important are the atmosphere and the soil and soil water.

2. The Salt-Weathering Hazard in Bahrain: Preliminary Review

Many of the preceding comments are particularly pertinent in Bahrain, where there is abundant evidence of the destructive effects of salt weathering on

buildings, roads and other engineering structures. This evidence can be briefly summarized and exemplified.

(a) Destruction of concrete as a result of corrosion and expansion of reinforcing bars emplaced in it (Plate V.1);

(b) Selective destruction of mortar in walls, especially near to ground level, probably as a result of both chemical changes to the mortar and salt crystallization processes (Plate V.2). It is a common observation that where building stones have been used which are in equilibrium with a saline-water environment, the stones are often relatively unweathered but the mortar which binds them is greatly affected. Such a building stone is beach rock, which was widely used in the construction of older buildings, especially near the coast;

(c) Destruction of concrete blocks and similar 'artificial' building materials (Plate V.3);

(d) Disruption of concrete foundations as a result, at least in part, of salt activity (Plate V.4);

(e) Disruption of paved-road surfaces, mainly cracking and pitting (Plate V.5)

Although 'salt weathering' normally appears to be responsible for such changes, it must be noted that other processes may be responsible for them in certain circumstances. These and similar changes are occurring at present, and often at a rapid rate. Two sets of observations confirm this assertion.

(a) Many recent engineering developments are already suffering from the effects of salt weathering. For example, the road from Az Zallaq to Al Mumattalah was paved in 1975 and began to show signs in certain locations of disruption only a month after its completion. Some of the concrete supports for the Alba cableway are already suffering from salt weathering. Perhaps the most spectacular example is the Salamaniya Hospital Nurses Home, where foundation deterioration and other problems related to salt weathering have caused the building to be condemned after a decade (Plate V.4).



PLATE V.1 Cracking of concrete as a result of corrosion
 (and expansion of a metal pipe emplaced in it
 (Awali).

PLATE V.2 Destruction of mortar in walls, without significant destruction of building stone near the base of houses in An Nuwaydirat.



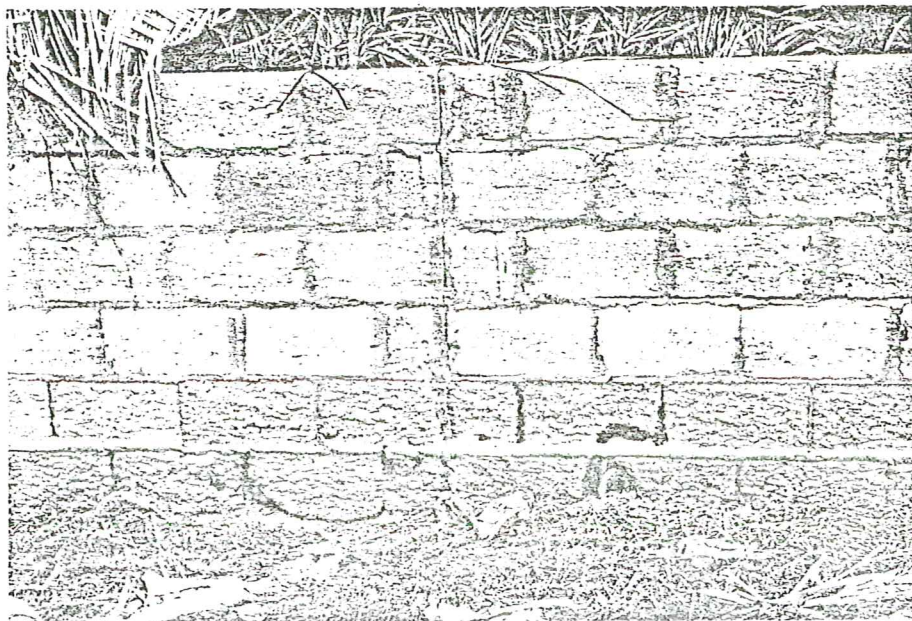
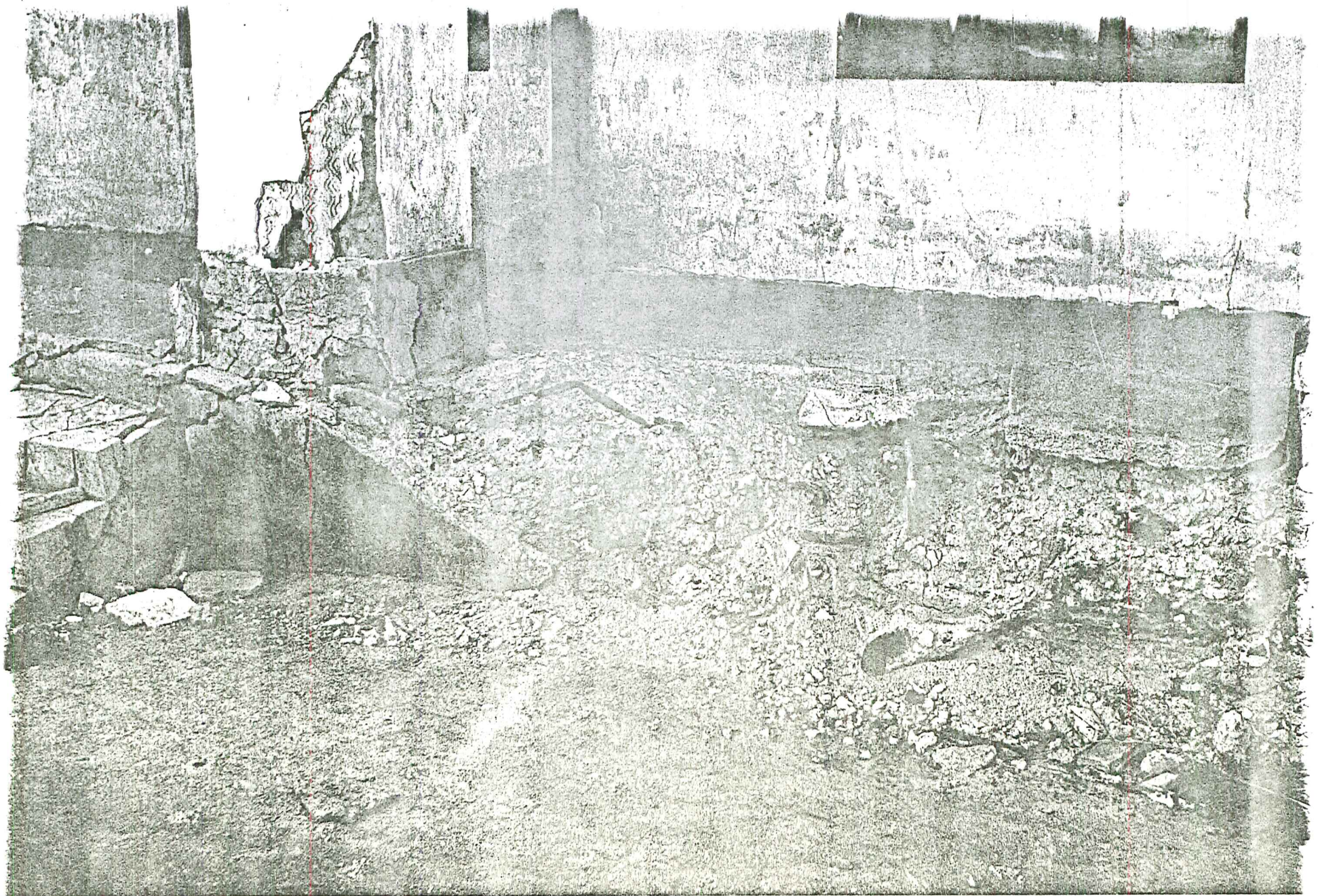


PLATE V.3 Destruction by salt-weathering of concrete blocks in walls of buildings at Samahij (Muharraq Island).

PLATE V.4 Destruction of foundations at the Salamaniya Hospital Nurse's Home, Al Manama.



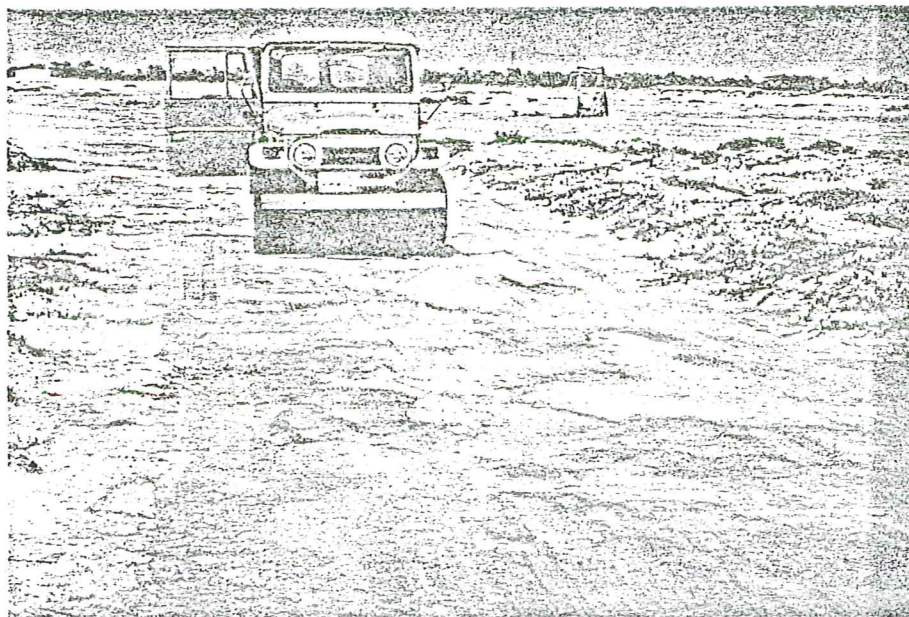


PLATE V.5 Disruption and destruction of 'paved'
road surface as a result of salt-
weathering and associated processes:
Near Sanad (G.R. 580920).

(b) In order to get an approximate idea of the rate of weathering on natural rock outcrops, a small field experiment was established in December, 1974. The site of the experiment was a location where it seemed likely that the rate of weathering would be most rapid - a cavern developed in Yellow Siltstone at the base of a cliff on the western side of a small enclosed depression near the Isa Alba road (reference 574913). The inner wall of this cavern is slightly damp, and the cavern surface is locally encrusted with salts. In order to determine whether the cavern surface is weathering at present, a 33cm wide band was sprayed with red paint from an aerosol can on December 16th, 1974. When the site was revisited on April 6th, 1975, approximately 75% of the paint had been removed, largely in the form of small flakes and silt (which had accumulated on the cavern floor). The disintegration had not been uniform: no painted surface remained at the innermost surface of the cavern characterized by salt efflorescence; over 80% of the painted surface had been removed from the cavern roof; and approximately 50% of the painted surface remained on the back wall (excluding the innermost section of salt efflorescence). There can be no doubt that the natural surface of the cavern is weathering very rapidly at present, and the flaky nature of the disintegration in association with salts and damp surfaces strongly points to salt weathering being the major process.

3. It is also clear that the salt-weathering hazard is more active in some areas of Bahrain than in others. For example, it appears to be relatively severe in the old township of Muharraq island, but the salt-weathering damage to buildings in Ar Rifa and the newer settlement of Awali is apparently relatively slight. Such contrasts are related to the materials used in construction, to the environment in which developments have taken place, to the age of the town and to the level of the water-table. The remainder of this part of the Report is devoted to an investigation of these variables. In the next sections, the nature of some natural materials used in the construction of engineering industries is examined, especially in terms of characteristics that may

relate to the salt weathering hazard. A subsequent section reviews the nature of the most important source of salts and saline solutions in buildings, roads etc, namely ground-water and its capillary fringe.

4. It must be emphasized that this study represents only a brief reconnaissance survey of a very important and complex problem which does not appear to have been studied in detail previously. The results must therefore be viewed with caution, and especially in the light of the stated assumptions.

V.3 NATURAL MATERIALS AND THE SALT WEATHERING HAZARD

1. Introduction

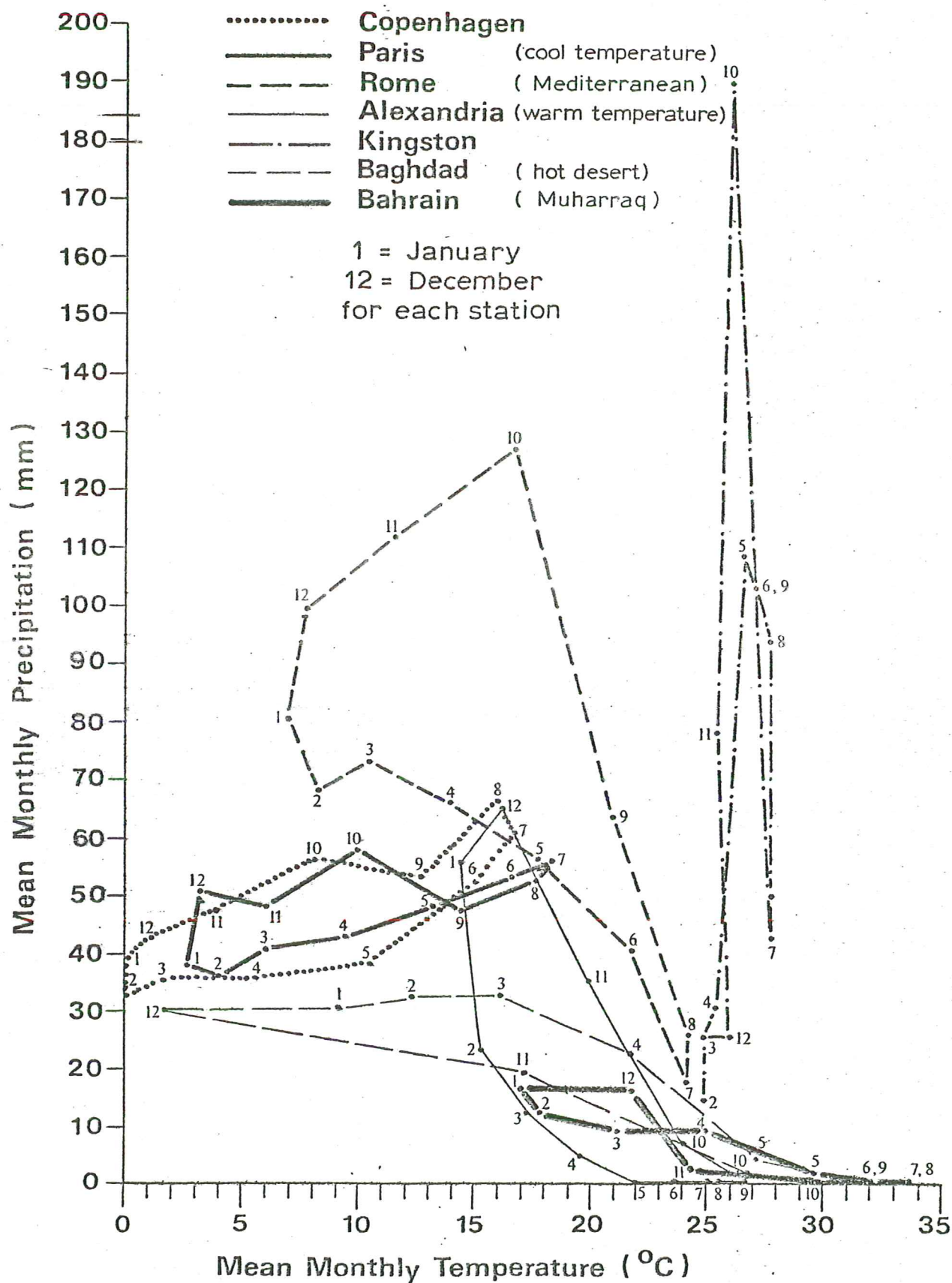
Only one aspect of this part of the problem is examined here - the susceptibility of selected indurated rocks to salt weathering. Other aspects of both indurated and unconsolidated rocks relevant to the salt-weathering hazard and other problems of the engineering and construction industries are reviewed in both volumes III and IV.

2. The Susceptibility of Selected Rocks to Salt Weathering Processes

Introduction and Methods

(a) Salt Weathering Test. The durability of rocks when subjected repeatedly to saturation with saline solutions and subsequent evaporation can be determined using a number of widely recognized standard tests. None of these tests, however, reflect closely the coastal-desert conditions encountered in Bahrain. In order to overcome this problem, a test of rock durability was devised which is more appropriate to Bahrain conditions (Goudie, Cooke and Evans, 1970). In this test, three 3cm cubes from each rock type examined were first weighed, and then immersed, one in distilled water (for control), one in a saturated solution of Sodium sulphate, and one in a saturated solution of Calcium sulphate, at 17-20°C for one hour. The sample cubes were then dried in an oven at 60°C for seven hours (a temperature approximating desert day-time surface temperatures), and then at 30°C for the remainder of each 24-hour cycle (a temperature approximating desert-surface night-time temperatures). The daily cycles were repeated for up to 40 days, or until the

Study of German



specimen disintegrated completely (whichever was the sooner). The weight loss in excess of one gram from specimen cubes was recorded after each cycle: weight loss from the original sample weight was used as the index of disintegration. Sodium sulphate was used because previous experiments have shown that it works relatively quickly; calcium sulphate was selected because it is one of the most important salts in Bahrain; and distilled water was used to provide a control on the experiments.

—This test was applied to fresh samples of 15 different rock types from Bahrain. The rocks were selected for various reasons - some are already used as aggregates or in 'fill'; some (e.g. the Yellow Siltstones) provide a contrast with the more durable rocks and some appeared to be relatively durable because they are positive relief formers and could therefore be potentially useful as building materials.

(b) Water Absorption Test. The British Standard test for water absorption (B.S. 1377), which gives a measure of rock open-pore porosity and thereby of susceptibility to weathering processes in which water is involved, was used. Three-centimetre cubes were immersed in de-ionised water for 24 hours, and were then lightly dried with a damp towel before being weighed (W_1). They were then dried in an oven at 105°C before being weighed again (W_2). Then

$$\text{Water Absorption Capacity (\%)} = \frac{W_1 - W_2}{W_2} \times 100.$$

(c) The Schmidt Hammer Test. The Schmidt Test hammer (Type N) is intended for non-destructive testing of concrete and natural materials (e.g. Yaalon, 1974). It measures the Rebound Number (R) which is related to hardness. R-values have been found to correlate with compressive strength. The hammer allows strength testing to be carried out rapidly, on a large number of samples, cheaply, and in the field. It thus offers considerable advantages in comparison with the more standard, slow laboratory techniques of strength determination. Clean, non-flaky, non-jointed, approximately flat surfaces were selected for field testing of rock types subsequently used in salt weathering tests. Ten R-values were recorded at each location, and the mean value (\bar{R}) was derived. Corrections to the R-values need to be made according to whether one is dealing

with vertical or horizontal surfaces. Correction values are shown on the nomogram attached to the instrument.

Results of the Tests

(a) Summary of Results. Table V.1 summarises data relating to types of material, water absorption capacity, rebound numbers, and the destruction of samples during sodium sulphate tests. The response of rock samples to sodium sulphate tests is shown in Figure V.2. Responses to calcium sulphate tests and to wetting and drying are listed on Table V.2. The relationships between resistance to Sodium sulphate weathering and hardness (rebound numbers) and water absorption capacity are shown in Figures V.3 and V.4 respectively.

(b) Comments on the Results. The samples tested had water absorption capacities which ranged from as little as 1.17% for Blue Askar (sample 16) to as much as 42.74% for the Yellow Siltstone (sample 2, Table V.1). Similarly rebound numbers determined with the Schmidt Hammer gave a range of from 57.50 (equal to a cube compressive strength in excess of about 11,000 p.s.i.; $7.5845 \times 10^4 \text{ KN/m}^2$) at the strongest end to about 12.80 (equal to a cube compressive strength of no more than about 1,000 p.s.i.; $0.6895 \times 10^4 \text{ KN/m}^2$) at the weakest end.

This variability in material character is reflected in the highly variable response to Sodium sulphate crystallization tests. Samples SW 10, 11, 12, 16, 7 and 5 (Table V.1) showed a relatively high degree of resistance to this process and might thus stand up well to crystallization of salts on exposed surfaces within the zone of salt-weathering hazard (see below).

On the other hand, other materials responded badly. This included, predictably, the highly porous and soft Yellow Siltstone (sample 2). However, samples of the so-called 'White Askar' from the Government quarry, in spite of both a high compressive strength and a low porosity ($R_N = 57.50$, W.A.C. = 1.55%) performed badly, totally disintegrating after only 19 cycles. Thus this material, selected as a concrete aggregate material on its inherently low chloride content, while not likely to cause concrete disintegration because of its chemical effect, might cause disintegration as a result of its susceptibility to salt crystallization, especially in areas subject to capillary rise

STRATIGRAPHIC EQUIVALENTS FOR TABLE V.1

<u>Old Terminology</u>	<u>New (B.S.M.R.S.) Terminology</u>
Yellow Siltstone	: Member of the Al Buhayr Carbonate Formation
Khobar Bedded Limestone	: Member of the Al Buhayr Carbonate Formation
Numulitic Limestone	: Member of the Foraminiferal Carbonate Formation
Miocene Limestone	: Ra's Al Aqr Formation (N.B. NOT MIOCENE)
Alat Dolomitic Cap	: Member of the Jabal Hisai Carbonate Formation
Flinty Khobar	: Member of the West Rifa Flint Formation
Sharkstooth	: Member of the Dil'Rafah Carbonate Formation

TABLE V.1

EXPERIMENTAL SALT WEATHERING TEST RESULTS

Sample No.	Material	Water Absorption % *	Rebound Number **	% Remaining ***	Cycles Elapsed	Rank
SW 2	Yellow Siltstone	42.74 (1)	27.5 (11)	0.00	7	14=
SW 3	Khobar Bed 3	9.79 (6)	31.8 (9)	0.00	9	13
SW 4	Numulitic Limestone	11.06 (5)	22.1 (12)	0.00	7	14=
SW 5	Crust on Bed 5 Bedded Limestone	4.15 (11)	34.3 (7)	75.20	50	6
SW 6	Khobar Bed 4	11.71 (4)	28.3 (10)	0.00	15	12
SW 7	Blue Askar	1.94 (13)	49.1 (3)	90.38	50	5
SW 8	Flinty Khobar	6.78 (7)	18.9 (16)	0.00	34	9
SW 9	Miocene Limestone	6.13 (8)	34.0 (8)	0.00	36	8
SW 10	Blue Askar	2.37 (12)	38.3 (6)	103.18	50	1
SW 11	Alat Dolomite	5.17 (9)	43.1 (5)	101.65	50	2
SW 12	Alat below cap rock	5.04 (10)	44.0 (4)	100.52	50	3
SW 13	White Askar (Govt. Quarry)	1.55 (14)	57.50 (1)	0.00	19	11
SW 14	Sharkstooth 9	21.07 (3)	17.10 (14)	0.00	23	10
SW 15	Sharkstooth 24	23.07 (2)	12.80 (15)	2.78	50	7
SW 16	Blue Askar	1.17 (15)	50.30 (2)	99.84	50	4

Notes

* Determined by British Standard Method (BS 1377). Figures in brackets are ranks.

** Determined by Schmidt Hammer (as described in text).

*** After treatment with Sodium Sulphate (as described in text).

N.B. The material names given above have been retained here in the old terminology. Their new equivalents, according to the stratigraphic terms given in Volume III are defined (where possible) overleaf.

FIGURE V.2 THE RESPONSE OF ROCK SAMPLES TO SODIUM SULPHATE TESTS

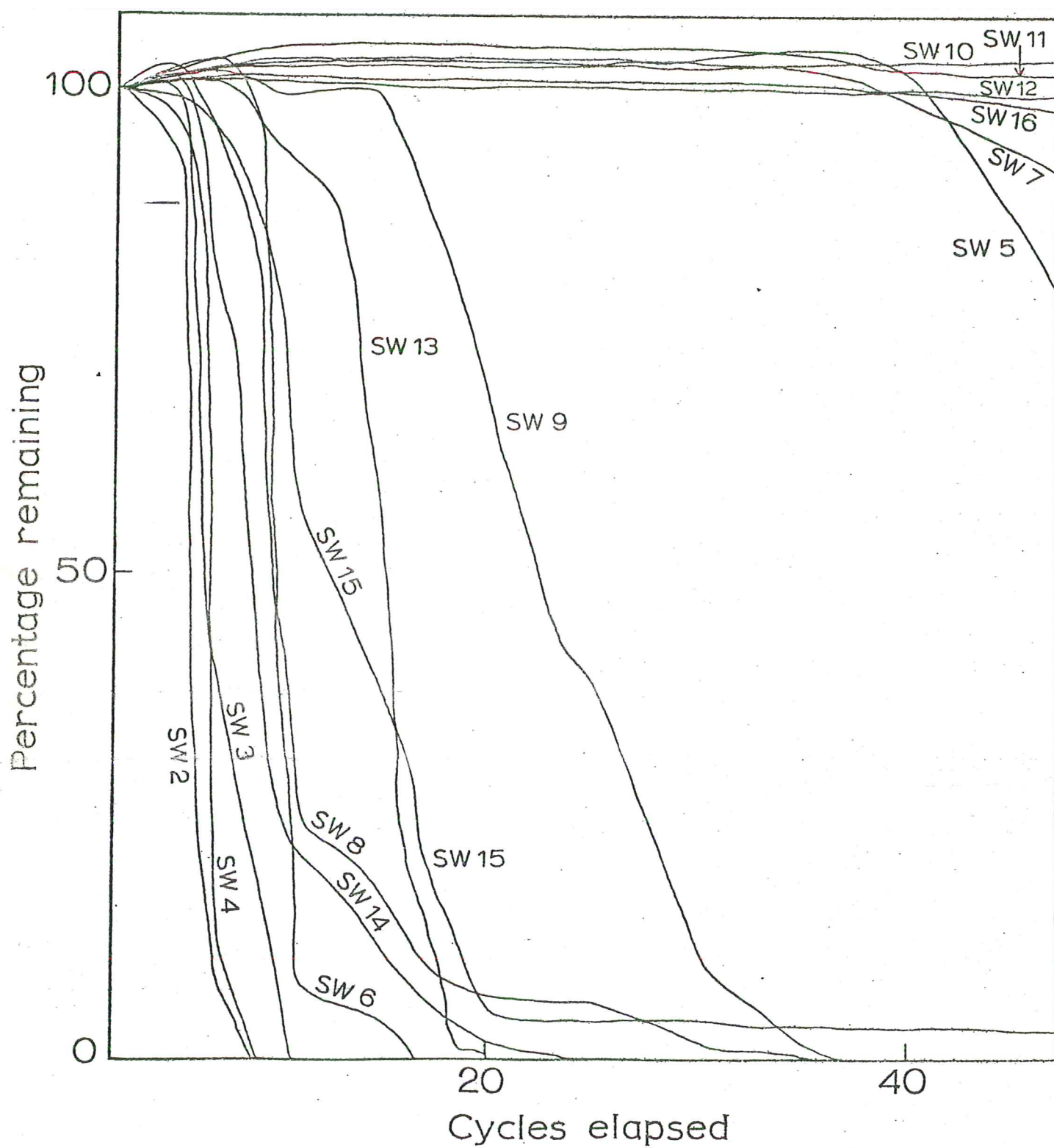


TABLE V.2

EXPERIMENTAL SALT WEATHERING TEST

RESULTS: SUSCEPTIBILITY TO WETTING AND DRYING AND CALCIUM SULPHATE
CRYSTALLIZATION

Sample No.		% Remaining after 40 cycles of wetting and drying	Calcium Sulphate crystallization
SW 2	Yellow Siltstone	89.15	98.24
SW 3	Khobar Bed 3	99.40	99.14
SW 4	Numulitic Limestone	98.83	98.83
SW 5	Crust on Bed 5 Bedded Limestone	99.80	99.89
SW 6	Khobar Bed 4	99.74	99.96
SW 7	Blue Askar	99.84	99.96
SW 8	Flinty Khobar	99.73	100.35
SW 9	Miocene Limestone	99.84	100.05
SW 10	Blue Askar	100.05	100.17
SW 11	Alat Dolomite	99.93	99.98
SW 12	Alat below cap rock	99.98	100.00
SW 13	White Askar (Govt. Quarry)	99.91	100.12
SW 14	Sharkstooth 9	98.34	99.74
SW 15	Sharkstooth 24	98.02	98.31
SW 16	Blue Askar	99.93	100.01

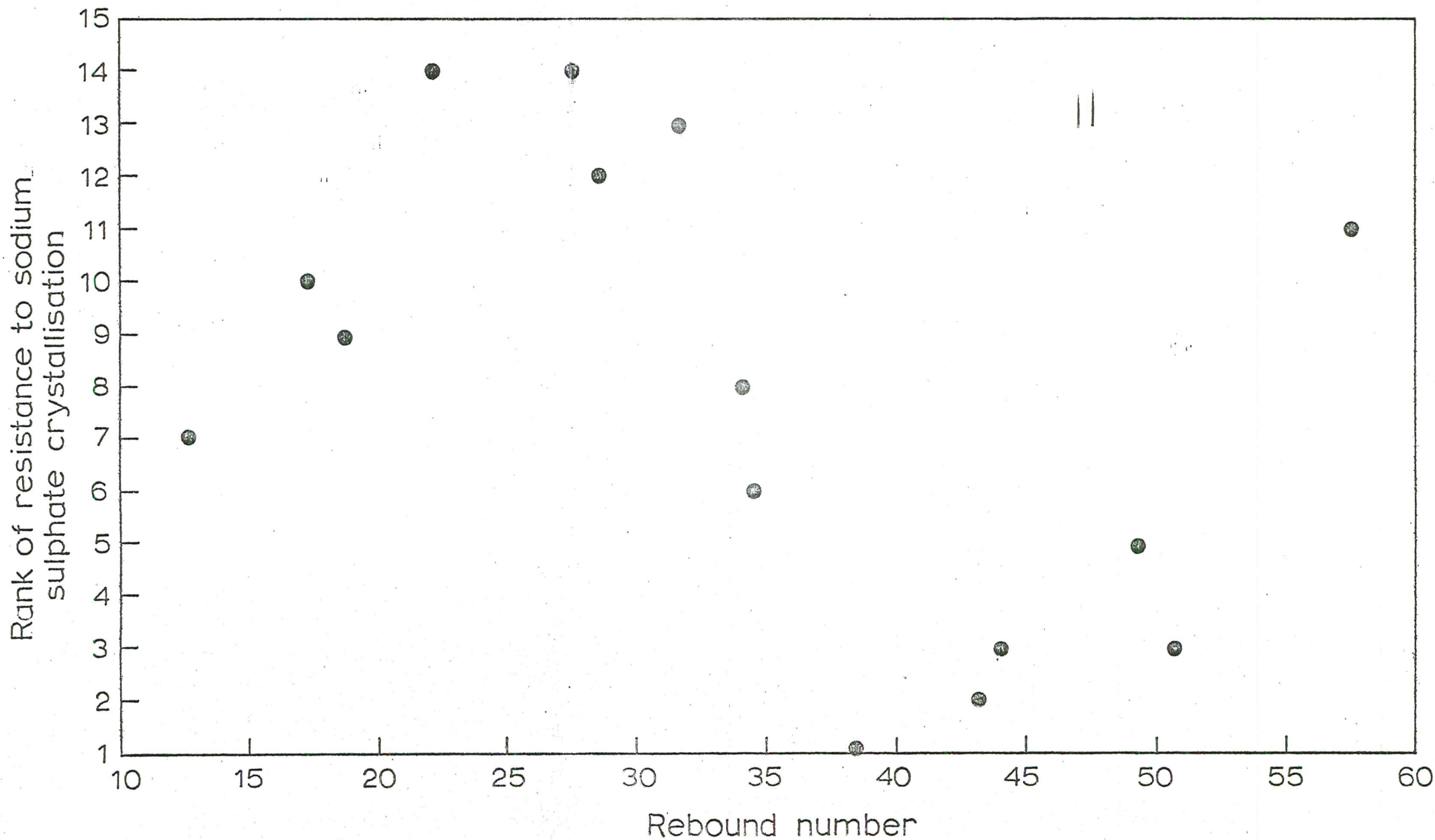


FIGURE V.3 THE RELATIONSHIP BETWEEN RESISTANCE TO SODIUM SULPHATE CRYSTALLIZATION AND HARDNESS (REBOUND NO.)

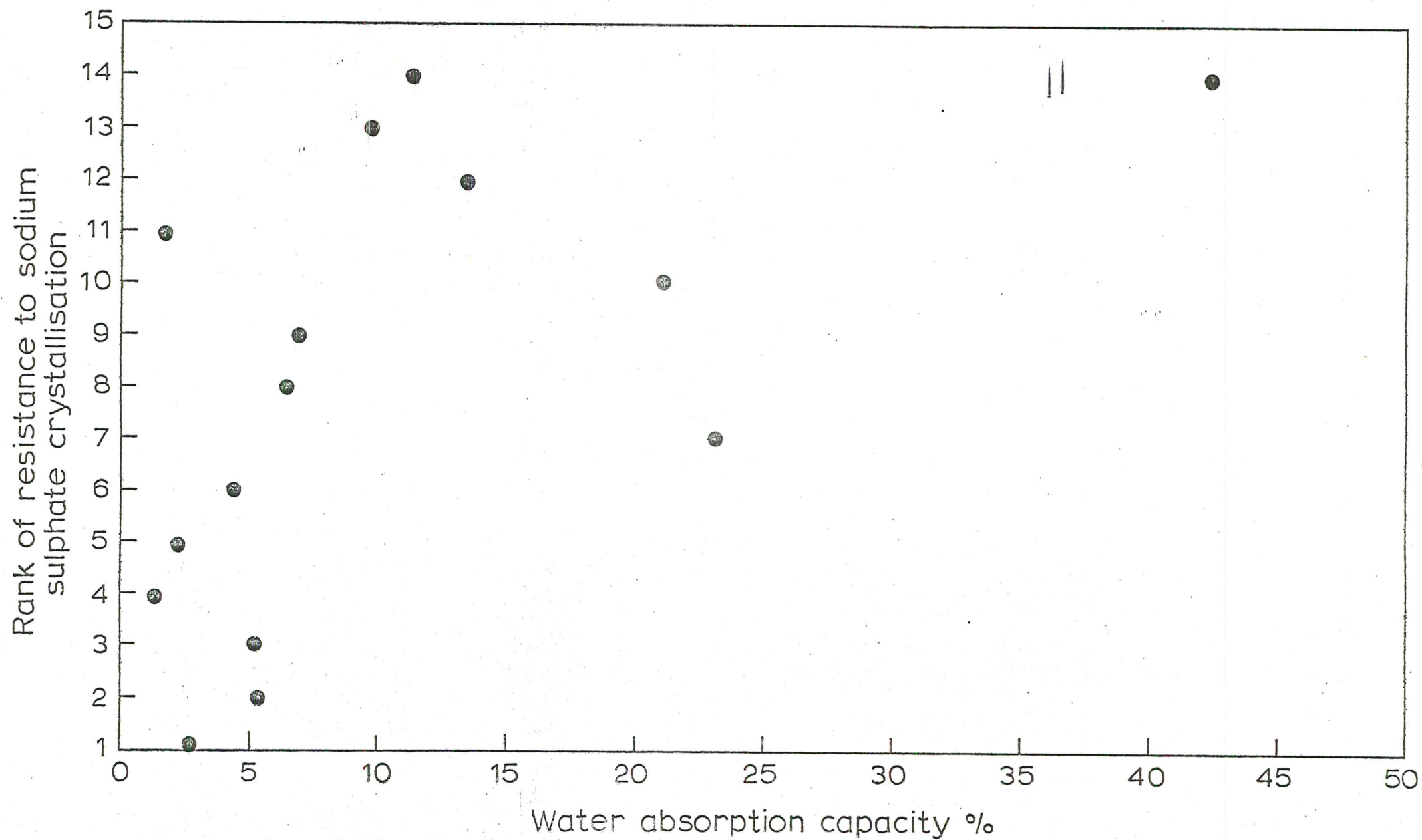


FIGURE V.4 THE RELATIONSHIP BETWEEN RESISTANCE TO SODIUM SULPHATE CRYSTALLIZATION AND WATER ABSORPTION CAPACITY

and evaporation of saline groundwater. (The performance of white askar under ASTM soundness tests is variable, but by and large much of it passes, and conditions in nature are, of course, generally less severe than those used in the laboratory tests).

All samples tested, with the exception of the Yellow Siltstone, responded well to the effects of simple wetting and drying, none of them experiencing a weight loss above 2% over 40 cycles. The effect of gypsum crystallization, probably because of the low solubility of calcium sulphate in water, was slight, and only three samples (SW2, SW4, SW15) showed any measurable response (Table V.2).

Neither the water absorption capacity nor the hardness of samples appear to offer good predictors of resistance to Sodium sulphate crystallization (see Figures V.3, V.4). It is thus probably desirable to subject materials to laboratory weathering tests rather than to rely upon surrogate properties of this type if the materials are to be used in areas subject to salt crystallization hazards.

V.4

GROUNDWATER, THE CAPILLARY FRINGE AND THE SALT-WEATHERING HAZARD

1. Definition of Terms

1. *Water-table* "the level to which groundwater rises in observation wells in free communication with the voids of the soil in situ" (Terzaghi and Peck, 1948, p.114)
2. *Groundwater* water in the zone of saturation beneath the water table and in the capillary fringe above it.
3. *Capillary fringe* the zone of saturated and partially saturated material above the water-table. Its upper boundary is called the height of capillary rise (and depends on the nature of the materials containing the water) (For a more detailed discussion of this important phenomenon, see Appendix V.1).

2. Introduction

Over much of the coastal plain of Bahrain, groundwater occurs close to or at the surface. Normally the water-table is at some depth below the surface. But over large areas the potential height of capillary rise is actually above the ground surface, so that surface material is damp, and the surface moisture suffers extensive evaporation. Two common relationships between groundwater, water-table, the capillary fringe and the ground surface are shown diagrammatically in Figure V.5 ; in (a) the height of capillary rise is below the surface; in (b) the potential height of capillary rise is above the surface.

If buildings, causeways, roads, pipelines, factories or other engineering structures are built in areas where groundwater occurs at or near to the ground surface, there is a strong probability that water may penetrate the structures. If the water is saline, and if it is evaporated so that salt crystallization occurs then damage may result. The primary purposes of this study are therefore:

- (a) to delimit areas where salt-weathering may be a hazard as a result of saline groundwater being close to or at the surface, and
- (b) to examine within the delimited areas spatial variations in the possible severity of the hazard.

It must be emphasized again that the results presented below represent only an initial exploration of the problem since a full analysis would require detailed experimentation, sampling and instrumentation over a longer time period in order to establish temporal as well as spatial variations.

3. Areas of Salt-Weathering Hazard

As a first approximation of the inland limits of the major coastal area of salt-weathering hazard arising from proximity of groundwater to the ground surface, the boundary separating places where capillary rise extends to the surface from those where it does not was plotted in the field (Figure V.6). The area where capillary rise extends to the surface is characterised in the field by the combined presence of three phenomena: damp surface material, puffy ground and salt efflorescence. These phenomena have to be used with caution to identify the boundary, because ground may become wet,

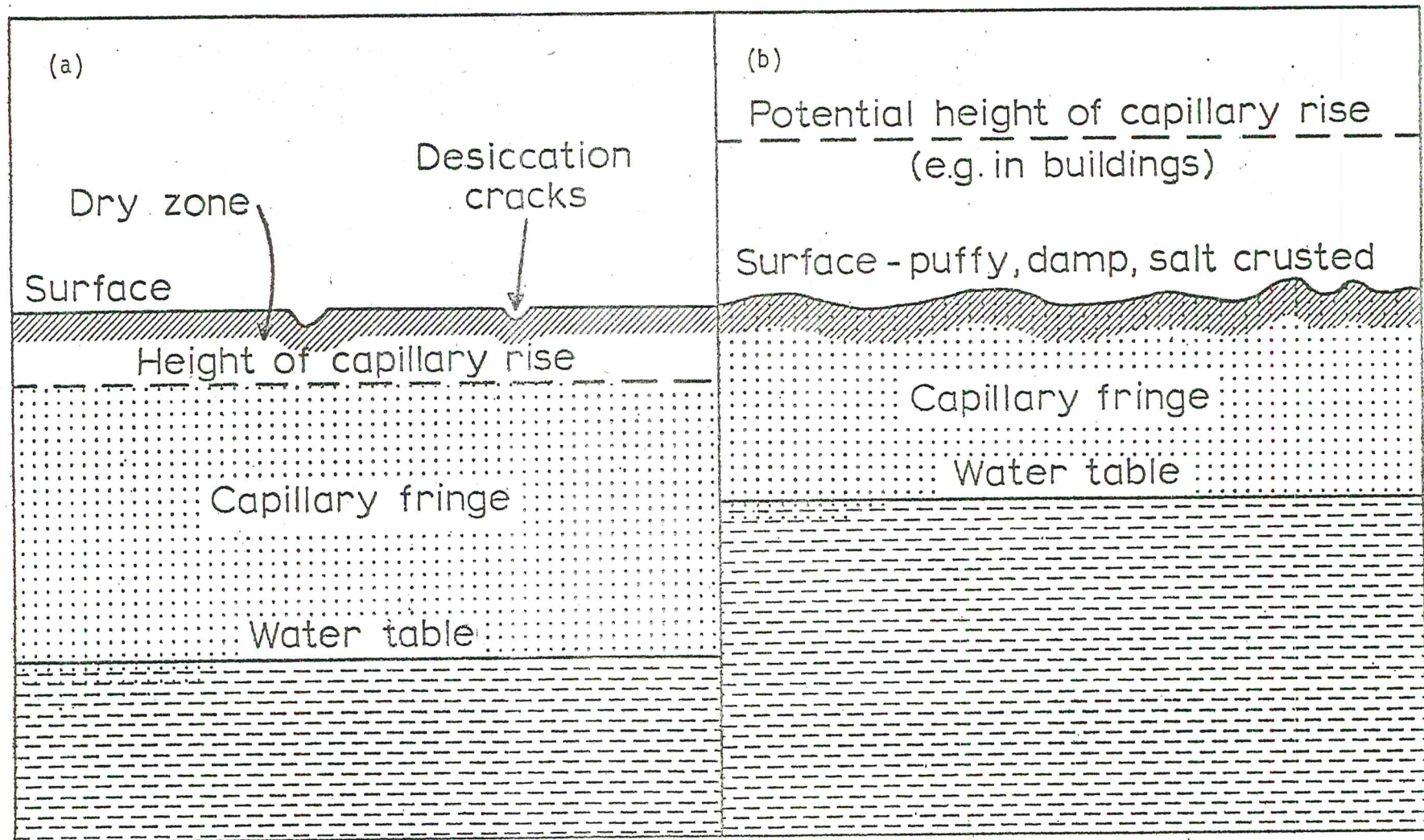
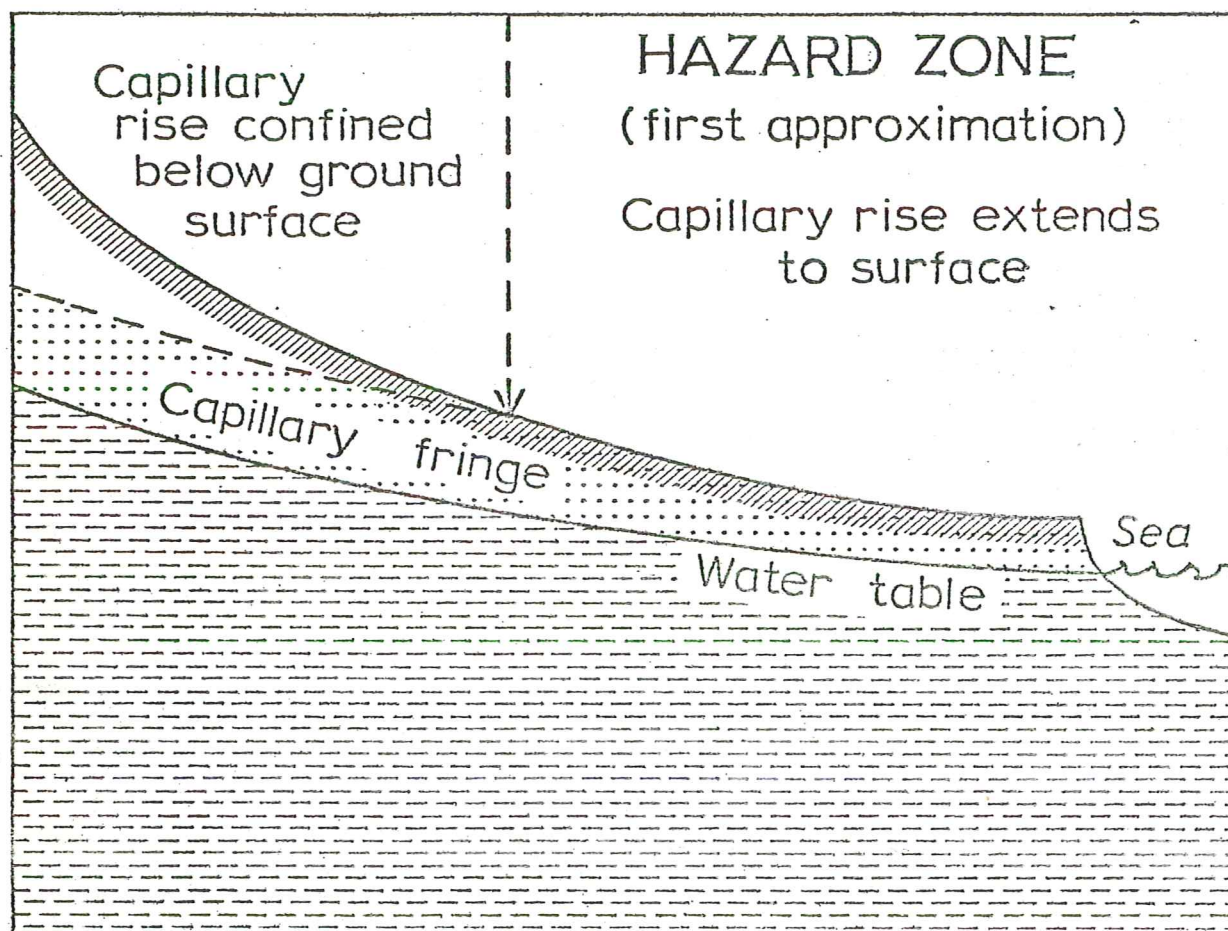


FIGURE V.5 THE RELATIONSHIP BETWEEN GROUNDWATER, WATER TABLE, CAPILLARY FRINGE AND GROUND SURFACE
a) Height of capillary rise below the surface
b) Height of capillary rise above the surface

FIGURE V.6 SCHEMATIC DIAGRAM ILLUSTRATING THE FIRST APPROXIMATION OF A HAZARD ZONE



puffy or saline for reasons other than capillary rise of water to the surface. In practice, the boundary is not difficult to locate, and it is shown on Map 7 (Map Volume A).*

Two comments should be made on this boundary. Firstly, it is only correct for April, 1975 - it probably changes position over time, especially in association with changes of water-table level. For example, the water-table has been falling in some inland areas of the zone over a period of years and it is therefore reasonable to assume that the zone of hazard has actually been slightly reduced in size.

Secondly, the boundary is not a satisfactory limit for the hazard zone because the foundations of any construction inland of it might extend to a sufficient depth to penetrate the capillary fringe below the surface and therefore suffer the effects of the hazard. Thus the boundary of the hazard zone is inland of that shown on Map 7, and theoretically should be located along the line where the height of capillary rise is always below the maximum depth of foundations. But because foundation depth is variable, height of capillary rise varies with materials (see Appendix V.I), and more information than was available from depths of over 2 metres is required to establish this boundary, an alternative approximation of the inland boundary of the hazard was adopted, namely the 10m contour, which is also appropriate for planning purposes.

4. Definition of a Planning Boundary

For planning and all other practical purposes, it can be said with certainty that land to seaward of the limit of surface capillary rise is potentially susceptible to salt-weathering problems. It is equally clear from field observations that almost all areas inland of that boundary which are susceptible to salt weathering as a result of proximity to groundwater occur below the 10-metre contour. This contour therefore provides a conservative inland limit for the hazard, and also provides a precise, easily used planning boundary. We

* NOTE: all maps are located in Map Volume A.

therefore recommend that the 10-metre contour should be used as a planning boundary for the groundwater salt-weathering hazard, in Bahrain, that any development below that altitude in the hazard zone should be preceded by a site assessment of the salt-weathering hazard, and that the conclusions of site assessments should be taken into account in regulating development.

5. Spatial variations in the Potential Severity of the Salt-Weathering Hazard within the Hazard Zone

One way of studying the spatial variations in the severity of salt-weathering problems arising from the proximity of groundwater to the surface in the hazard region might be to survey and classify the severity of damage to existing structures. The approach was rejected mainly because:

(a) it is generally difficult, and sometimes impossible, to determine the age of affected buildings, and thus the period during which salt-weathering has been active is unknown, and

(b) the effect of salt-weathering is strongly influenced by the materials used in construction and the design of the structures - both of which may vary greatly from place to place.

An alternative approach, and the one adopted in this survey, is to determine the spatial variations of these environmental variables which influence or are assumed to influence the severity of the hazard within the hazard zone. The environmental variables selected, and the reasons for selecting them are as follows:

(a) Depth to water-table Below Ground Surface. It is assumed that, in general, the deeper the water-table is below ground surface, the less the penetration of groundwater into foundations, buildings, etc. and the less the damage from salt-weathering is likely to be. For example, a building which is entirely above the height of capillary rise is unlikely to be affected, whereas a building constructed on a surface where the water-table is at ground level is likely to suffer partial or full saturation by saline groundwater in its walls up to the full height of capillary rise and it is likely

to be severely affected by the hazard. Put another way, it is assumed that the damage caused by salt-weathering associated with groundwater is approximately proportional to the area of the structure affected, and that the area of the structure affected is proportional to shallowness of the water-table. This general assumption needs to be qualified, of course, in the light of the type of materials above the water-table because, as is shown in Appendix V.I, the height of capillary rise will locally vary with the characteristics of such materials.

(b) The Quality of Groundwater. It is assumed that, in general, the greater the salinity of groundwater, the greater is likely to be the damage caused by salt-weathering. In addition, spatial variations in the ionic composition of solutions may play a part in influencing spatial variations of the hazard.

6. Method

Within the zone of salt-weathering hazard defined on Map 7 147 points were selected to provide a relatively comprehensive and uniform sampling design. At each of the 147 points, the depth to water table below the surface was determined, the height of capillary rise noted (where it was below the surface), a water sample was collected, and the nature of surface and near-surface material was recorded. Additional observations were made of water-table level and materials at 39 other locations. All observations were made and all samples were collected in April, 1975, and the results (Appendix V.II) relate only to conditions prevailing at that time. Particular attention was given to collecting water samples which had not been contaminated by irrigation water or surface runoff and had not been subjected to surface evaporation. Samples were collected from wells, pits and auger holes. Measurements of water-table in pits and auger holes were only made after a reasonable period of time had elapsed to allow an equilibrium level to be attained.

The electrical conductivity was recorded (at the Survey base in Manama) using a single meter. The ionic analysis of water samples was carried out

at Imperial College, London. All field and laboratory data were put onto punched cards, and the distribution maps were prepared using a SYMAP programme on an IBM 360 Computer. These maps are in Map Volume A.

7. Analysis of Results

(a) Depth to Water-Table (Map 8) The following qualifications about Map 8 should be noted.

(a) The data refer only to water-table depth below ground surface, and are not adjusted to any horizontal datum plane (such as sea level). Thus, for example, if a pit was dug through a sand dune, depth to water-table might be considerably greater than in another pit adjacent to the dune, although the absolute altitude of the water-table might be the same in both cases.

(b) In this, as in all similar figures, the isolines are interpolated between sample points and present a generalised, most probable pattern based on values at those points only. The isolines are therefore only predicted values, not actual values for any location, and the predictions depend inter alia, on the pattern of sample points.

(c) The water-table record is not related to any single aquifer - a sample may refer to different aquifers in the Damman beds, or may refer to a perched water table etc.

In general depth to water-table increases from the coast inland. At the inland limit of surface capillary rise (Map 7) the predicted depth to water-table (Map 8) varies considerably - mainly as a reflection of variation in surface materials - but field observations show that it is almost always over one metre, and commonly over 2 metres. At the 10 metre contour, the depth to water-table normally exceeds 2 metres, although it is somewhat shallower in the western part of the area than in either the north or the east). In many localities along the coast, the water-table is very near to the ground surface - often at less than 0.75 metres. In terms of this criterion alone, therefore it appears that the salt-weathering hazard is likely to be greatest near to the coast, and to diminish inland.

The relatively simple pattern of increasing depth to water-table inland is complicated by a number of distinctive features:

- (a) the scarp-and-dip slope of the Jabal Hisai (Refinery) Limestone Formation in the northwest (approximately from Dumistan to Al Diraz) provides a salient of higher ground in the northern lowlands where depth to water-table is relatively great;
- (b) some dune areas locally cause the water-table to be somewhat deeper below the ground surface (e.g. 510010 and 466850);
- (c) the basins on the northeastern flanks of the Upper Damman Backslope (shown on the 1:10,000 geomorphology maps in Map Vol. C) have floors which are relatively close to groundwater level, and in a few places on these floors capillary water is, at least seasonally, at the surface.

(b) The Height of Capillary Rise. Within the coastal zone of capillary rise (Figure V.6), the height of capillary rise is, by definition, normally above the ground surface, and it can often be seen as the upper limit of dampness in buildings within the zone. As indicated in Appendix V.I, the height of capillary rise depends primarily on the nature of the materials above the water-table, and in general it is inversely proportional to the void ratio and to particle size. Empirical observations in Bahrain by members of the Survey team confirm this assertion.

(i) In sandy soils height of capillary rise is commonly between 1 and 1.5m above the water-table, (e.g. sites at 469878, 462981, 461899, 564938).

(ii) In loamy soils (comprising sand, silt and clay), capillary rise normally exceeds 2.00m but is less than 3.00m (e.g. sites at 528934, 565943, 591898, 502931, 582927, 579926, 590897, 556950).

The distribution of sandy and loamy soils is described in Volume VI. These observations indicate that for most practical purposes it can be assumed that, even in the finest-grained materials, the height of capillary rise is normally less than 3.00m above the water-table. Estimates of the height of capillary rise using Terzaghi and Peck's formula (Appendix V.I), and assuming reasonable values for void ratio and particle size, are similar to these field observations.

The height of capillary rise in building materials emplaced in the hazard zone is, of course, variable, and was not surveyed in this study: it is a problem that deserves attention.

There are a few areas below the 10m contour that appear to be above the height of capillary rise. In general these are too small to appear as major anomalies on Map 8, but they include some of the sand-dune areas along the western and northern coasts, the margins of the Jabal Hisai (Refinery) Limestone Formation outcrop, north of Dumistan and in the east of the island, the alluvial fringes of the lower Dammam Backslope and bedrock areas northwest of Sanad. Within these areas, which have not been mapped systematically from the point of view of salt-weathering, there remain undeveloped sites which are relatively free of potential salt-weathering problems. One such site is on the dip slope of the Jabal Hisai Formation east of the Alba smelter (e.g. 617853), the base of the lower Dammam Formation Backslope affords similar locations. The potential of such sites for development deserves further investigation. On the other hand, some areas within the hazard zone where the height of capillary rise is below the surface (such as the sand-dune areas) should not be considered hazard-free because the capillary fringe would probably be penetrated by foundations.

(c) Electrical Conductivity of Groundwater (Map 9). Specific conductance (conductivity) is a measure of a conductor to convey an electric current. In the case of water, it is related to the concentration of ions present and to the temperature at which measurement is made. It is usually measured in micromho/cm. Electrical conductivity is related directly (but in a non-linear way) to the concentration of solutions, but it gives no indication of the nature of the substances in solution. It is possible to convert readings of electrical conductivity into estimates of salinity (e.g. in parts per million), but only the original readings are used in this study because empirical conversion factors (which have a considerable range) depend on a greater knowledge of soluble compounds in the samples than is at present available.

The assumption behind the measurement of electrical conductivity in the context of the salt-weathering hazard is that the magnitude of the hazard is directly related to the salinity of groundwater, and thus to its electrical conductivity. It is assumed, then that electrical conductivity readings provide a simple first approximation of the relative intensity of the salt-weathering hazard in the context of groundwater quality. Map 9 shows the pattern of electrical conductivity of groundwaters in Bahrain based on samples collected in April, 1975. As with previous diagrams, qualifications are necessary in interpreting these data:

(i) electrical conductivity of groundwater may vary with time - perhaps as a result of evaporation locally concentrating solutions or, on a longer-term basis, as a result of salt-water incursion into formerly relatively fresh groundwater in coastal areas.

(ii) electrical conductivity readings may reflect groundwater contamination by pollutants. As far as possible, samples that may have been subjected to such local influences have been rejected, but some results could be affected, for example, by dilution with irrigation water.

As Map 9 shows that most of the lowland fringe within the hazard zone has groundwater characterized by relatively low electrical conductivity (normally less than ^{38,000} 3.8×10^4 umhos/cm). But five areas of relatively high conductivity stand out. The three areas in the east of the island - on Muharraq island, adjacent to the creek of Sha'bayn al Rhodra 520970), and on the island of Sitrah and adjacent coastal areas on the mainland - are all probably associated with the intrusion of salt water into groundwater aquifers and with the evaporation of marine groundwater. Such is certainly the case in the sabkha environments of southern Muharraq island and the Sitrah region. The two areas of relatively high conductivity in the west - near Dumistan and Al Qurrayyah - while they are both associated with the flanks of the Jabal Hisai outcrop (dip slope) are more difficult to explain. These five areas are, according to the assumption stated above, likely to be areas of relatively high salt-weathering hazard.

(d) Ionic Concentrations in Groundwater (Maps 10 - 15). Experimental

work of salt-weathering (e.g. Goudie, Cooke, and Evans, 1970) demonstrates that certain salts are more effective weathering agents than others. For example, sodium sulphate is commonly more effective than sodium chloride. Thus it would be valuable to know the spatial distribution of salts that would be precipitated from solutions within the hazard zone. To determine precisely which salts would form from the evaporation of the chemically complex groundwater samples is a major laboratory task quite beyond the scope of this survey. As an intermediate step in the analysis of the hazard, the ionic concentrations in the samples were determined, and their spatial distributions are recorded in Maps 10 - 15. It has yet to be demonstrated experimentally that there is a direction correlation between the absolute and relative quantities of particular ions (although it seems to be a reasonable assumption), so little importance is attached to these distributions at present. It is sufficient to note that, not surprisingly and with the possible exception of Ca^{++} , the areas of highest ionic concentrations in each case coincide with the areas of highest electrical conductivity - on Muharraq island, on Sitra island and the adjacent coast between Sanad and the oil refinery, the area in the western flanks of the Jabal Hisai Formation dip slope in the north-west, and between Dumistan and Buri. (Preliminary analysis of the relative concentrations of ions has been carried out but, because the significance of the relevant ratios in the context of salt-weathering is as yet imperfectly understood, this analysis has not been included in the report).

(e) Intensity of the Hazard in the Hazard Zone. On the basis of the preceding discussion, it can be hypothesized that the intensity of the salt-weathering hazard associated with groundwater in the delimited hazard zone is directly related to

- (i) the shallowness of groundwater and
- (ii) the electrical conductivity of groundwater.

Map 7 has been derived on the basis of these assumptions and on the

additional assumption that the two variables are of exactly equal importance. These assumptions are open to question, but they serve as a basis, in the absence of additional data, for a first approximation of hazard intensity.

Map 6 identifies a number of areas where it is predicted that the hazard is likely to be most intense:

- (i) Muharraq island, especially in the south-east;
- (ii) The creek area adjoining Sha'bayn al Rhodra;
- (iii) Sitrah and the adjoining coastal fringe of the mainland between Ra's Sanad and the oil refinery;
- (iv) The area around Dumistan;
- (v) Western flank of the Jabal Hisai Limestone Formation (Alat) dip slope north of Al Hamalah.

As areas (iv) and (v) arise from only relatively few sample points they should be further examined to justify their continued inclusion in this list.

8. Conclusions and Recommendations

1. This study represents a preliminary reconnaissance survey of the salt-weathering hazard in Bahrain. In view of the very considerable economic importance of the hazard and the present deficiencies in knowledge of it, further research should be encouraged. This research should include an examination of:

- the physical and chemical effects of salt on locally produced building materials, including concrete;
- the effects of differences in absolute and relative variations in ionic concentrations in groundwater, and the effects of differences in the absolute and relative quantities of salts likely to be precipitated from groundwater subject to evaporation;
- the role of climatic conditions;
- the ways in which salts become incorporated into engineering structures before, during and after construction;
- the durability of all potentially usable building stones and aggregates.
- changes in the groundwater-table due to abstractions by wells, recharge and seawater inflow into lowered areas of groundwater.

2. The 10 metre contour may be regarded as the upper boundary of the salt-weathering hazard as it relates to groundwater and capillary rise. It is strongly suggested that any development within the hazard zone (i.e. below 10m a.s.l.) should be preceded by a site assessment of the salt-weathering hazard, and that the results of such assessments should provide the basis for appropriate modifications to development proposals designed to reduce or eliminate the effects of the hazard.

3. Within the zone of salt-weathering hazard (Map 6) it is predicted that some areas are more hazardous than others. Particular care in construction and other developments should be exercised in the more hazardous zones - especially on Muharraq island, Sitrah island and the mainland adjacent to it, and in the zone bordering the creek of Sha'bayn al Rhodra.

4. Where practicable, further urban and industrial development should be located outside of the hazard zone. Many potentially suitable construction sites are available, and in some areas (notably in Isa Town) only slight changes to development plans are required in order to make considerable long-term economies. Within the hazard zone there remain a few sites where the height of capillary rise is sufficiently deep below the surface to make salt-weathering an unlikely hazard. One such site is on the dip slope of the Jabal Hisai Formation to the east of the Alba smelter and close to the sea as well as on the Upper Dammam Backslope.

5. Greater care should be taken in the selection and use of natural materials in the construction industry. Salt-weathering and related experiments show that the durability of materials is extremely variable, and materials suitable for construction purposes in one context are unsuitable in the context of salt-weathering. It is probably desirable that materials apparently suitable for use in construction should first be subjected to laboratory weathering tests, especially because surrogate properties of materials assumed to be related to weathering performance do not appear to be very satisfactory. The analysis of salt-crystallization effects on different rock types could profitably be extended to include

(a) some more resistant rocks lower in the stratigraphic succession
(e.g. the Rus) and

(b) a selection of concrete aggregates used in construction.

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APPENDIX V.I

ADDITIONAL NOTES ON THE CAPILLARY FRINGE

ADDITIONAL NOTES ON THE CAPILLARY FRINGE

The capillary fringe is so important in the coastal areas of Bahrain that it deserves some additional comment. Where the material above the water-table consists of soil or unconsolidated sediments, it is characterized by voids of variable sizes that are intercommunicating and present, in effect, a network of voids. Such material may be invaded by groundwater from below as a result of the attraction between the sides of the voids (material surfaces) and the water molecules combined with the surface tension of the water. The lowest part of the void network will become completely saturated, whereas in the upper part water will occupy only the smallest voids (Terzaghi and Peck, 1948; Figure V.7).

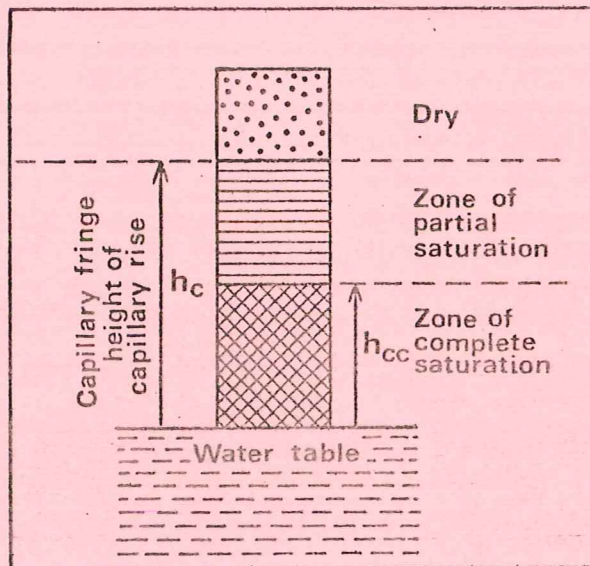


Figure V.7 Diagram to illustrate the capillary rise of water in a column of initially dry sand (after Terzaghi and Peck, 1948).

The upper limit of capillary rise is commonly, and especially in hot desert environments and where it is above ground level, a locus of evaporation where crystalline salts may be precipitated. Thus if capillary water extends in to foundations, etc., salts may be precipitated in buildings, with serious consequences. The upper limit of dampness in the walls of so many buildings in Bahrain is, in effect, the upper limit of capillary rise.

The height of capillary rise depends on the nature of the material above the water-table. In general, as particle size decreases, void size also decreases, and the height of capillary rise increases (Terzaghi and Peck, 1948). For example, Terzaghi and Peck (1948) suggest that:

$$h_c = \frac{C}{eD_{10}}$$

where h_c = height of capillary rise

e = void ratio

D_{10} = "effective size", in which 10% of particles in the grain-size analysis are finer, and 90% are coarser than this value.

C = an empirical constant that depends on grain shape and surface impurities, and ranges between 0.1 and 0.5 sq. an.

Thus the height of capillary rise can be expected to be considerably higher in clays, for example, than in sands (Table V.3).

TABLE V.3

Soil Type	Capillary rise range (m)
Sand	0.10-1.00
Silt,	1.00-10.00
Clay	10.00

Source: Scott and Schoustra, 1968, p.37.

It should be noted that the absolute altitude of the height of capillary rise can vary through time as the result of:

- (a) daily, seasonal, annual or longer-term changes of water-table (arising from, for instance, climatic change, sea level change, changes in groundwater recharge:discharge ratios, and the extraction of water for irrigation and other water-supply purposes);
- (b) changes in the nature of materials above the water-table (e.g. compaction or cementation); or
- (c) the emplacement of 'artificial' materials (such as concrete, which will also influence the height of rise).

APPENDIX V.II

GROUNDWATER DATA FROM BAHRAIN

Bahrain Surface Materials Resources Survey, 1976

GROUNDWATER DATA FROM BAHRAIN

Water Sample Number	Grid Reference	Ground water level (m.)	$\mu\text{mhos/cm (x10}^4\text{)}$ conductivity	gm/cc					
				Chlorine Cl^-	Sulphate SO_4^{--}	Sodium Na^+	Potassium K^+	Calcium Ca^{++}	Magnesium Mg^{++}
A	E N B	C	D	E	F	G	H	I	J
58	527969	1.20	1.75	5.1	2.49	2.9	0.14	0.81	0.39
66	511950	0.75	2.26	8.2	0.68	4.1	0.16	0.78	0.34
69	504941	1.05	5.95	25.2	2.50	12.0	0.42	2.60	1.20
84	493963	1.30	3.70	12.6	3.75	7.1	0.37	1.07	0.93
88	470968	0.70	0.67	1.6	1.84	0.6	0.04	0.68	0.14
99	491958	6.00	0.99	2.1	1.40	1.3	0.07	0.61	0.18
210	493814	0.35	2.80	7.2	3.93	4.2	0.23	0.76	0.83
125	484867	1.10	0.86	1.7	1.89	1.0	0.07	0.63	0.18
219	550962	1.00	4.28	16.4		8.8	0.05	1.69	1.12
10-555	498818	1.25	1.12	2.6	2.34	1.7	0.16	0.61	0.26
10-560	498832	1.60	2.40	7.5	2.80	4.3	0.21	0.95	0.45
10-562	490830	0.80	1.49	4.1	2.52	2.2	0.10	0.83	0.38
10-563	480829	0.60	2.21	6.5	3.46	3.6	0.20	0.89	0.64
10-564	501843		0.80	1.9	1.40	1.1	0.06	0.52	0.19
10-567	493842	0.80	1.19	3.0	2.34	1.7	0.11	0.75	0.30
10-571	484850	1.10	1.55	4.7	3.08	2.7	0.12	0.84	0.53
10-572	480850	0.50	0.58	1.5	0.72	0.6	0.05	0.30	0.12
228	576935	0.95	0.51	1.4	0.41	0.6	0.04	0.24	0.16
232	620065	0.25	0.79	1.0	0.39	0.6	0.07	0.20	0.08
238	654041	0.80	0.90	2.5	0.82	1.4	0.07	0.39	
257	590932	2.25	0.52	1.4	0.44	0.8	0.04	0.24	0.09
260	589903	1.15	1.13	3.3	0.70	1.8	0.06	0.41	0.16
10-573	473871	0.26	2.65	8.0	3.68	4.8	0.28	0.79	0.71
10-575	475872	0.90	3.11	10.0	3.58	5.6	0.42	0.86	0.90
10-576	469878	1.70	2.29	6.9	3.10	5.1	0.28	0.76	0.59
10-577	472897	1.30	7.90	41.2	8.55	22.5	1.40	1.02	2.78
10-578	482900		16.00	90.1	11.55	49.0	2.08	1.06	5.63
10-579	496931	1.25	0.91	2.7	1.06	1.3	0.05	0.53	0.14
10-580	493934	2.50	0.74	2.1	1.00	1.1	0.06	0.36	0.12
10-581	494951	5.00	0.83	2.2	0.98	1.2	0.08	0.45	0.17
10-582	502931	2.70	1.56	5.9	0.71	3.0	0.12	0.64	0.27
10-583	582931	1.00	0.77	1.7	1.56	0.9	0.05	0.70	0.12
10-584	577934	1.60	2.62	8.3	2.20	4.4	0.20	1.13	0.53
10-585	582927	2.10	2.46	7.5	3.19	4.2	0.26	0.94	0.53
10-586	579926	2.30	0.71	2.3	0.96	1.0	0.08	0.44	0.13
10-587	592905	1.00	1.30	3.9	1.06	2.0	0.10	0.53	0.23
10-588	590897	2.90	0.93	2.6	1.06	1.4	0.07	0.51	0.17
10-589	517930	6.00	1.55	5.4	1.20	2.8	0.12	0.75	0.29
10-590	514938	2.55	3.30	11.8	2.00	5.7	0.21	1.61	0.50
10-591	526954	1.55	1.28	3.9	0.44	1.9	0.08	0.45	0.18
10-592	520937	1.73	3.39	11.5	2.38	5.7	0.21	1.44	0.70
10-593	534957	2.50	3.60	12.6	0.53	6.7	0.22	0.97	0.42
10-594	491958		1.28	2.6	1.36	1.2	0.07	0.60	0.18
10-595	496962		0.73	1.8	0.54	0.9	0.06	0.32	0.12

A	B	C	D	E	F	G	H	I	J
10-596	485972	7.50	0.66	1.3	1.08	0.8	0.05	0.41	0.15
10-597	486978	2.40	1.96	5.3	2.68	2.7	0.15	0.95	0.48
10-598	488985	2.93	0.82	1.8	1.57	1.0	0.07	0.48	0.17
10-599	556950	2.15	1.19	3.2	1.44	1.6	0.05	0.59	0.23
10-601	611858	1.80	3.63	12.4	3.08	6.6	0.23	1.13	0.74
261	589898	2.40		2.8	1.01	1.6	0.07	0.44	0.18
262	591898	2.00	5.75	21.5	4.45	1.8	0.05	1.49	1.27
402	549976	0.40	0.87	2.2	0.90	1.2	0.06	0.39	0.17
10-602	509947	0.55	3.26	11.4	1.63	5.9	0.24	1.07	0.58
10-603	518992	3.20	0.88	2.1	1.53	1.1	0.07	0.55	0.18
10-604	510999	3.20	0.88	1.9	1.47	1.0	0.06	0.58	0.16
10-605	510006	4.00	0.70	1.6	1.29	0.9	0.06	0.51	0.14
10-606	503003		0.40	1.0	0.41	0.5	0.03	0.22	0.07
10-607	505985	2.50	1.19	2.6	1.80	1.4	0.12	0.65	0.24
10-608	515984	2.15	2.80	8.9	3.5	4.9	0.28	0.97	0.71
10-609	525968	0.60	1.65	5.3	2.20	2.8	0.30	0.85	0.40
10-610	544971		0.62	1.8	0.53	0.9	0.05	0.30	0.10
10-611	555981	1.49	0.52	1.3	0.55	0.7	0.05	0.27	0.09
10-612	459919	1.80	0.78	1.8	1.71	1.0	0.07	0.55	0.17
10-613	452918	0.90	0.85	1.8	2.29	1.0	0.07	0.64	0.20
10-614	455917		0.97	2.5	1.68	0.8	0.10	0.51	0.22
10-615	452929	0.35	5.90	22.8	3.05	12.1	0.63	0.77	1.37
10-616	457942	0.90	17.00	112.0	12.25	63.7	2.06	1.41	5.58
10-617	459957	1.00	0.56	1.2	1.00	0.7	0.04	0.42	5.62
10-618	455954	0.69	1.42	3.8	2.29	2.1	0.14	0.64	0.37
10-619	457956	0.35	8.90	37.2	15.05	21.0	1.26	1.21	4.12
10-620	473769	1.62	0.68	1.6	1.44	0.9	0.05	0.54	0.15
10-621	464964	1.25	0.78	1.7	1.75	1.0	0.06	0.62	0.18
10-622	470975	3.40	0.73	1.6	1.51	0.8	0.07	0.52	0.18
10-623	470977	3.10	0.67	1.5	1.25	0.9	0.06	0.45	0.14
10-624	487987	3.20	0.76	1.8	1.46	1.0	0.07	0.49	0.18
10-625	483003		3.60	12.2	4.35	5.3	0.37	1.23	1.08
10-626	464976	3.00	0.81	1.7	2.15	0.9	0.11	0.69	0.19
10-627	575013	2.00	2.22	6.5	1.34	3.8	0.15	0.44	0.42
10-628	581013	1.00	0.78	1.7	1.10	1.0	0.12	0.41	0.15
2794	618925	0.90	7.90	33.9	4.70	18.2	0.83	1.61	1.86
2798	518925	0.90	3.65	12.5	3.00	7.1	0.22	1.07	7.77
285	557885		0.19	0.2	0.20	0.1	0.02	0.80	0.03
405	557994	1.10	0.89	2.3	1.08	1.3	0.03	0.48	0.18
411	555978	0.20	0.46	1.2	0.41	0.7	0.04	0.22	0.08
412	556977	0.60	0.45	1.1	0.39	0.7	0.04	0.23	0.08
206	500845	5.50	0.87	1.9	1.44	1.1	0.07	0.50	0.19
296	461943	0.29	1.14	2.4	3.14	1.6	0.18	0.58	0.36
297	460898	1.20	1.83	5.3	2.65	2.9	0.15	0.73	0.46
6602	595914	0.60	9.55	47.8	5.80	26.5	0.48	0.74	2.98
6606	602905	0.68	16.00	102.0	10.10	57.0	1.75	1.16	6.18
6610	603902	0.73	17.00	118.0	10.70	38.0	2.12	1.16	6.78
6615	605898	0.92	19.00	166.0	5.20	95.0	2.97	1.44	7.64
6621	611894	0.89	9.70	48.7	5.50	27.0	0.98	1.65	2.50
6625	615885	1.04	12.00	64.0	6.15	36.0	1.44	1.34	3.53
6631	624874	0.44	15.00	93.6	8.55	49.5	1.89	1.12	5.10
6636	598897	0.87	5.00	20.5	4.20	11.5	0.45	1.22	1.17
6639	629886	0.73	14.50	86.5	7.65	49.0	1.68	1.23	4.75
6645	514962	1.88	5.45	22.3	4.95	6.5	0.65	1.28	0.66
6650	523964	1.00	2.95	10.7	2.50	5.1	0.28	1.27	0.54
6651	528965	0.73	12.00	63.4	4.80	12.0	1.37	1.60	1.28
6652	535966	0.85	5.75	23.4	3.55	5.2	0.55	0.53	0.54
6653	621063	0.36	2.80	9.9	2.25	5.2	0.22	0.62	0.74
6656	625060	0.46	2.40	5.5	2.05	2.9	0.12	0.53	0.44
6660	635058	0.60	7.90	36.7	3.05	13.5	0.86	0.89	1.48

A	B	C	D	E	F	G	H	I	J
6668	654042	0.90	7.90	36.1	4.40	5.2	0.93	0.72	0.74
6670	656035	0.66	2.80	9.6	2.95	5.1	0.20	0.48	0.89
6671	645037	0.74	19.00	127.0	9.45	72.0	2.34	1.21	7.12
6678	641039	0.70	3.50	13.0	1.45	7.0	0.37	0.67	0.66
6878	645049	0.67	2.20	6.9	3.85	3.6	0.13	0.81	0.78
6880	634062	1.29	0.73	1.5	2.34	0.8	0.08	0.60	0.23
6899	540985	1.21	2.48	8.0	3.55	4.3	0.23	0.92	0.62
6904	540980	0.76	1.51	3.3	1.39	1.7	0.08	0.57	0.22
6907	542976	1.00	3.78	14.2	3.30	7.5	0.27	1.19	0.80
6910	544973	0.90	7.13	2.0	0.74	1.1	0.06	0.36	1.25
6913	545972	0.73	5.05	30.6	3.15	11.5	0.43	0.59	1.35
8067	456989	0.50	0.62	1.5	0.96	0.9	0.05	0.38	0.15
8089	458978	0.61	2.73	9.1	3.55	5.0	0.44	0.91	0.73
8017	468979	0.60	0.63	1.3	1.74	0.7	0.04	0.70	0.10
8073	472970	1.22	1.09	2.8	2.28	1.7	0.12	0.70	0.23
8070	464978	0.81	2.35	7.6	3.15	4.1	0.29	0.60	0.50
8100	453952	0.40	2.18	6.8	2.09	3.7	0.20	0.55	0.47
8102	458948	0.63	1.40	3.9	2.77	2.3	0.17	0.65	0.36
8106	462945	0.42	2.68	8.5	4.05	5.5	0.30	0.74	0.53
8110	455907	0.53	0.62	1.4	1.80	0.9	0.08	0.38	0.16
8114	459908	0.86	0.83	2.4	0.88	1.5	0.06	0.26	0.13
8117	463909	0.44	5.75	24.5	4.00	12.5	0.55	1.27	1.52
8130	453987	0.99	1.13	3.0	2.13	1.6	0.14	0.59	0.26
8132	458986	0.56	0.65	1.2	2.20	1.7	0.14	0.61	0.28
8137	477863	0.51	0.93	2.3	1.98	1.3	0.08	0.63	0.24
8140	480865	1.02	1.66	4.3	3.12	2.6	0.20	0.78	0.46
8143	484866	0.60	1.62	5.4	3.03	3.3	0.27	0.76	0.42
8145	489865	0.92	1.30	3.6	2.47	2.0	0.10	0.79	0.32
17-002	594917	0.40	7.20	29.7	4.15	17.2	0.63	0.63	1.98
17-004	598911	0.50	13.50	75.8	7.98	38.7	1.23	1.15	4.23
17-008	602905	0.74	18.00	130.0	12.10	70.5	2.32	1.05	7.92
17-017	622878	0.61	13.00	117.0	5.00	62.5	2.82	1.35	5.32
17-018	617897	0.62	1.86	4.9	0.83	2.7	0.15	0.35	0.33
17-021	620905	0.75	18.00	128.0	9.48	69.5	2.37	1.22	7.25
17-027	519963	1.40	5.01	20.5	3.10	10.2	0.52	1.80	1.10
17-029	532967	0.48	7.40	25.4	4.05	16.8	0.64	1.83	2.02
17-032	627063	0.70	2.18	7.7	1.42	4.1	0.17	0.56	0.46
17-033	630063	0.46	11.00	56.9	6.60	30.0	1.18	1.53	3.50
17-034	646054	0.43	4.12	17.0	1.73	8.8	0.48	0.52	1.16
17-037	651033	0.82	14.80	88.4	4.65	48.0		0.67	6.00
17-098	563996	0.37	3.35	11.9	3.88	6.3	0.36	1.67	1.00
17-101	564992	0.68	1.30	3.8	1.78			0.69	0.24
17-144	579936	0.91	11.00	54.9	5.78	30.0	1.19	1.16	3.23
	518990	2.00							
	491008	0.60							
	494007	0.95							
	525965	0.90							
	506964	1.25							
	508946	1.30							
	508945	1.15							
	503927	2.50							
	481970	4.00							
	488967	5.00							
	489989	1.20							
	495963	1.70							
	471978	0.95							
	495952	5.00							
	525953	1.30							
	499949	1.20							
	491854	0.90							

A	B	C	D	E	F	G	H	I	J
	496838	1.45							
	496862	1.50							
	472899	0.70							
	461907	0.20							
	455920	0.40							
	465925	0.30							
	456934	0.70							
	461943	0.40							
	464940	0.70							
	456908	0.40							
	534938	1.80							
	530929	1.80							
	523934	2.30							
	496843	1.20							
	561954	0.60							
	564958	0.40							
	555961	0.30							
	565943	2.20							
	575933	1.50							
	580917	1.80							
	588918	0.50							
	499975	2.30							

APPENDIX V.III

NOTES ON THE SYMAP CONTOURING PROGRAM

APPENDIX V.III

NOTES ON THE SYMAP CONTOURING PROGRAM

Several of the maps in Map Volume A (Maps 6, 8-15) were produced using the SYMAP program provided by the Laboratory for Computer Graphics and Spatial Analysis, Harvard University. This program accepts as input information the value of a variable at a set of data points with known co-ordinate locations, and uses these to calculate values at all points on a rectangular grid.

The data set consisted of 242 points. Groundwater water level was available for 233 of these points; conductivity for 163 points, and ion content for 147 points (although the content of one or two ions was not recorded in a few cases). 147 points were used in all map runs, except for groundwater (where an additional 39 points were used). The program calculates a value for points on a rectangular grid, based on a weighted average of the data points within a set radius of the point. The radius was set such that, on average, seven data points are found on the initial search. In addition, it was specified that a minimum of four and a maximum of ten data points be used for interpolation.

Four barriers were set up in the study area such that data points on one side of the barrier could have no effect on values for points on the other side. These prevented interpolation between islands and the mainland, and across bays, for example. The barriers ran between the following co-ordinate locations :

- (a) 545970 to 640960
- (b) 580050 to 640980 to 645030
- (c) 590940 to 615917 to 615907 to 636870
- (d) 629049 to 620010

After values were calculated over the map, the range of values was split into classes, and a map produced on the line printer by printing a symbol or

combination of symbols to represent each of the classes. The maps produced measured 24" x 20.5". The coastline and the boundaries between classes were then plotted on an overlay to produce the final map.

The eleven maps produced in this way involved the following electives (described in A User's Guide to SYMAP and SYMVO, edited by D.T. Muxworthy, Edinburgh, 1972) :

1. Size 24" x 20.5" ;
3. Five class intervals;
4. Zero was taken as the minimum permissible value for the calculation of class intervals;
6. The class intervals were constructed by dividing the range of values at data points into equal classes;
8. Contour lines were not plotted on the map;
15. Maps were printed at 6 rows per inch and 10 columns per inch;
18. Zero and blank values were disregarded;
23. The location of data points with zero and blank values were not shown.

Three further maps were produced in which the class intervals were in the ratio 1 : 1 : 2 : 2 : 2. This gave more detailed information at the low end of the range, in which the bulk of the observations were concentrated. The map of 'hazard intensity' represents a simple combination of the values for groundwater level and conductivity at each point. Values for the two variables were scaled so that the total range for each was the same, and groundwater level readings were subtracted from the maximum depth recorded so that high values for each variable represented the greatest potential hazard. The two variables were then summed, and the result scaled to provide a potential range between 0 (least hazardous) to 100 (most hazardous). If groundwater level is denoted as \underline{x} , and conductivity as \underline{y} , the map depicts

the quantity

$$\left(7.50 - x + \frac{7.50y}{19} \right) \frac{100}{15}$$

7.50 being the maximum groundwater depth recorded and 19.00 the maximum conductivity reading.