LYCÉE LOUIS MASSIGNON
ليسيه لوي مسينيون

ÉTABLISSEMENT EN GESTION DIRECTE

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HELAL&PARTNERS
ARCHITECTS I ENGINEERS I TOWN PLANNERS

RENOVATION OF BLOCK B' FOR FRENCH SCHOOL (LYCEE LOUIS MASSIGNON)

CONCRETE REPAIRS AND STRUCTURAL REINFORCEMENT

PLOT (26_27), SECTOR (E40)
ABU DHABI ISLAND
EMIRATE OF ABU DHABI
UNITED ARAB EMIRATES

VOLUME 5 – Part 6 of 7

M/s eForce Inspection Consultancies
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eFORCE Inspection Consultancies
(CENTER FOR ENGINEERING STUDIES & CONSULTANCY SERVICES)

إيفورس لاستشارات الكشف على الأنشاءات
(مركز الدراسات الهندسية والخدمات الإستشارية)

CONDITION ASSESEMENT OF THE GYMNASIUM, SWIMMING POOL, AUDITORIUM & CLASSROOMS BUILDING IN THE LYCÉE LOUIS MASSIGNON SCHOOL, ABU DHABI, UAE

Submitted to	**M/s Al Hilal Engineering Consultants**
Reference code	**eFORCE/1104/24**

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Prepared by	Verified by	Rev. Number	Date
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1 INTRODUCTION

1.1 General

eFORCE Inspection Consultancies (Center for Engineering Studies and Consultancy Services) was requested by M/s Al Hilal Consulting Engineering to inspect and assess the Gymnasium, Swimming Pool and Auditorium and report on the current structural condition of the structures under consideration.

A WORKING TEAM from eFORCE has carried out visual inspection of buildings, assess the quality of concrete, and conduct concrete tests to investigate the current situation.

1.2 Scope of the Consultancy Work

The scope of work includes the following tasks required to complete the structural assessment of the existing structures:

- Visual inspection of the accessible structural elements to identify the defected elements under consideration.
- Conduct semi destructive and non destructive tests to study the concrete and steel of the different elements.
- Analyze the test results along with the visual inspection observations to conclude the overall condition of the floor under consideration.
- Provide a technical report covering all the findings.

2 THE STRUCTURES DESCRIPTION

For the Auditorium and Playing Area

The auditorium consists of a wooden roof supported on columns and the playing area (Dojo) building consists of a hordi slab supported on hidden beams and ribs on columns.

For the Gymnasium

The Gymnasium consists of a wooden roof supported on concrete columns.

For the Swimming pool

The swimming pool consists of a wooden roof supported on concrete columns.

3 INVESTIGATION AND TESTS

3.1 Approach to Inspection

The inspection program targets studying the existing reinforced concrete elements in terms of performance and durability of its materials. This is achieved by

- Initial Site Survey
- Investigation, Sampling and Testing
- Final Site Investigation

3.2 Initial Site Survey

An initial site survey was made to carry out visual inspection, data and information collection on the condition of the buildings. Detailed planning, including structural consideration, was undertaken prior to the full survey in order to optimize all aspects of the work. Accordingly, the scope of work for overall site concrete sampling and testing works was prepared.

3.3 Investigation, Sampling and Testing

To determine the physical and mechanical properties of concrete, a comprehensive in-situ and laboratory test program was prepared. Samples for physical, mechanical and chemical analysis were obtained from representative structural elements to cover the area under investigation. Also, non-destructive testing was performed. Such sampling and testing works included:

a) Drilling of concrete cores.
b) Determining concrete cover to reinforcement as obtained from the Cover Meter surveys carried out using a digital cover meter.
c) Measuring the depth of Carbonation on freshly broken surfaces of the concrete.
d) Conduct the half-cell potential tests to provide the probability of steel corrosion.
e) Conduct the resistivity test of concrete to provide the rate of steel corrosion.
f) Extract samples from the concrete for chloride content.
g) Conduct Ultrasonic Pulse Velocity tests to determine the concrete quality

Samples collected on site will be subsequently taken for further analysis to establish the following:

- Visual examination and description of the core samples.
- Compressive strength and density of concrete in the existing structural members as obtained from the tested core samples.
- Chloride level inside the concrete from the laboratory tests on the concrete.

3.4 Final Site Investigation

In addition to the sampling and testing works, the WORKING TEAM carried out further visual inspection to confirm the outcome of the testing results. A summary of the WORKING TEAM's detailed survey observations and test results will be incorporated in section 4.

The test locations are presented in figures 3-1 to 3-3. While the test locations description are presented in table 3-1

Table 3-1
Test locations description

Test No.	Test Location
B1	Basement Floor Column
B2	Basement Floor Column
B3	Basement Floor Column
G1	Ground Floor Column
G2	Ground Floor Column
G3	Ground Floor Column
G4	Ground Floor Column
G5	Ground Floor Column
G6	Ground Floor Column
G7	Ground Floor Column
G8	Ground Floor Column
G9	Ground Floor Column
G10	Ground Floor Column
G11	Ground Floor Column
G12	Ground Floor Column
G13	Foundation
G14	Foundation
F1	First Floor Column
F2	First Floor Column
F3	First Floor Column

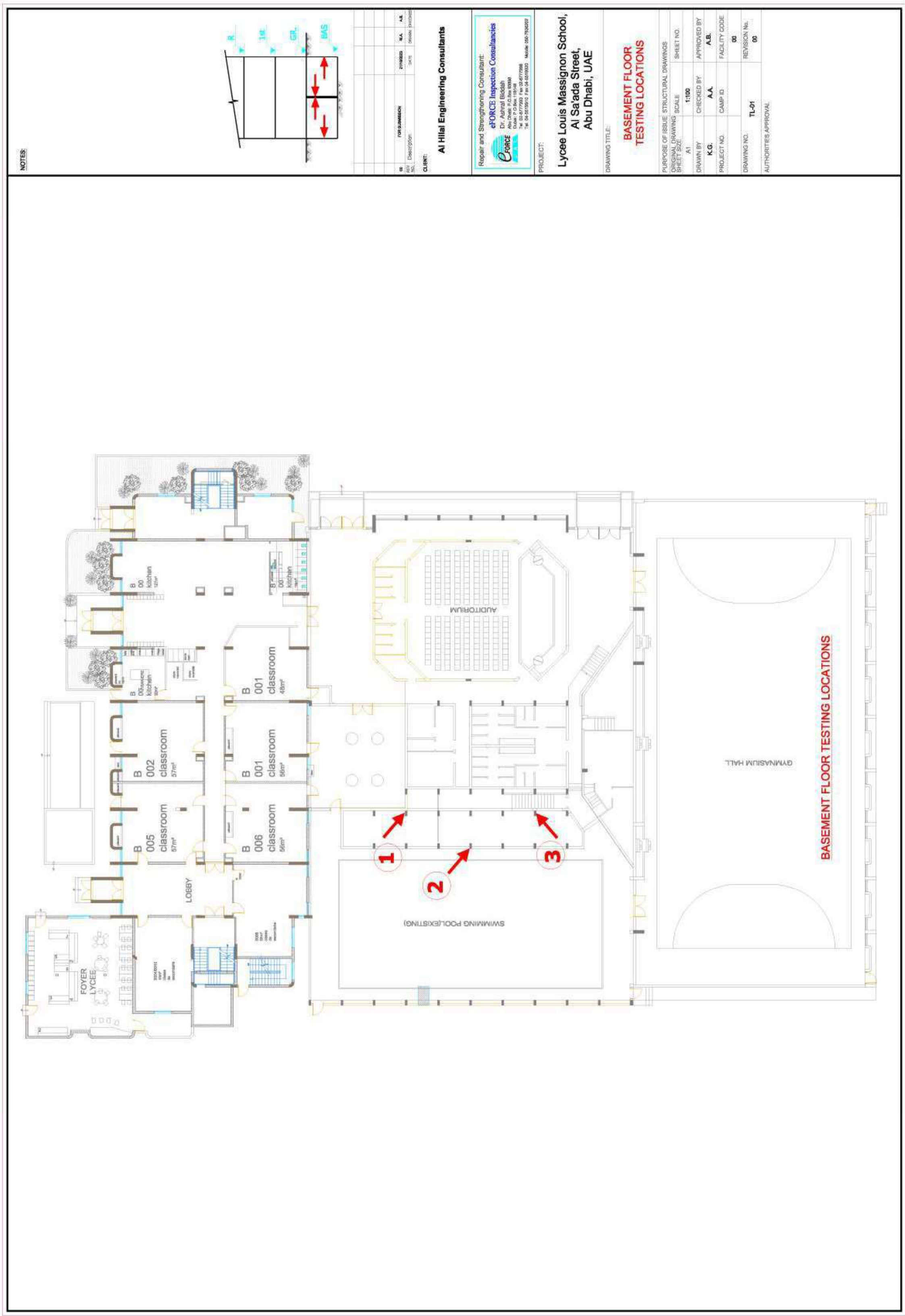

Figure 3-1 Basement floor test locations

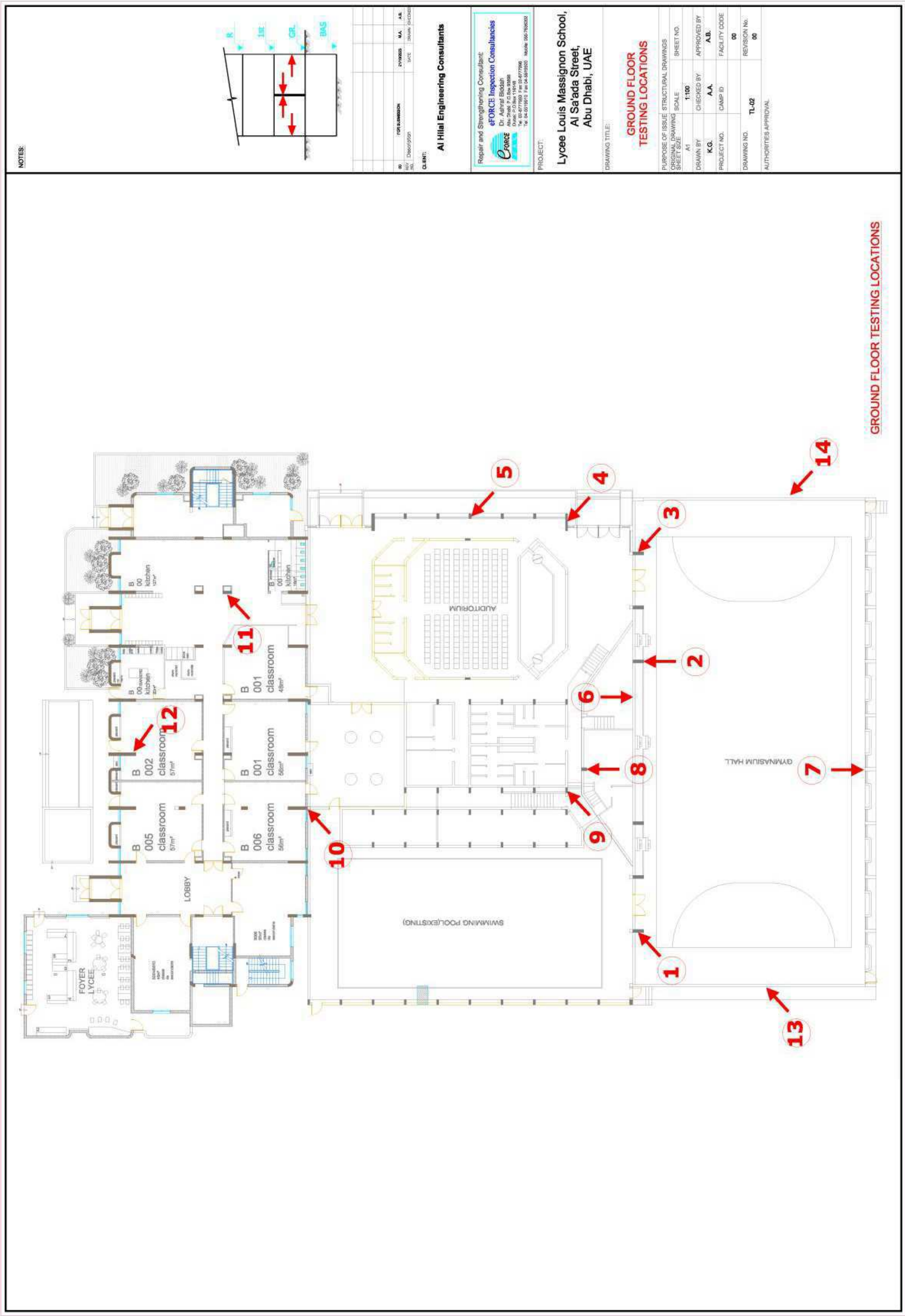

Figure 3-2 Ground floor test locations

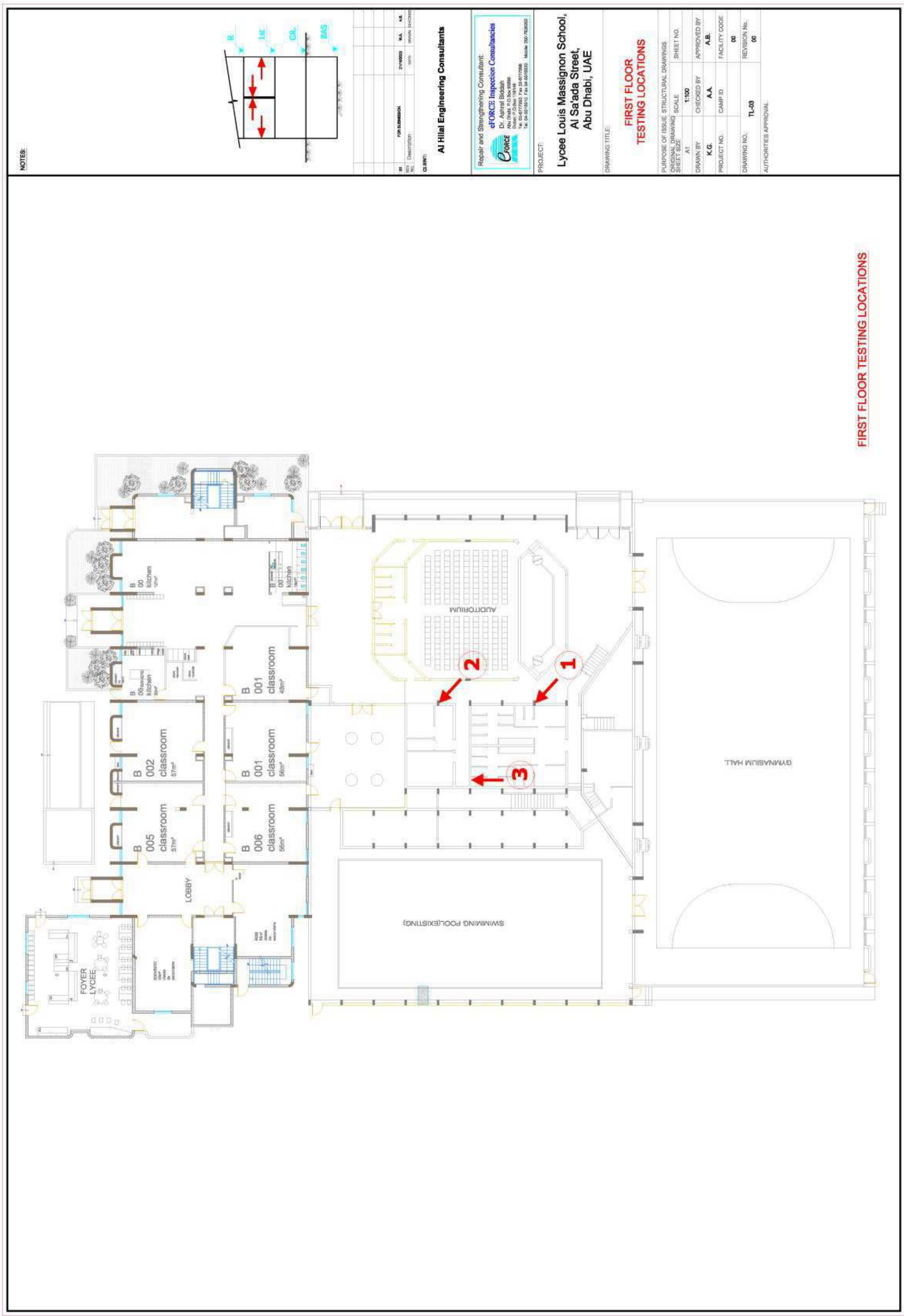

Figure 3-2 First floor test locations

4 EVALUATION OF INVESTIGATION & TEST RESULTS

4.1 Visual Inspection

A visual inspection of the structures under consideration was carried out to determine the extent of visible cracking, Delamination or other damages and defects in the area. The visual inspection observations can be summarized as follows:

- For the Gymnasium

  1- Delamination of the concrete cover in Columns, retaining wall below stands and in stands soffits
  2- Cracks between block walls and concrete elements
  3- Cracks in retaining wall below stands and in stands soffits
  4- Dampness in block walls
  5- Dampness in concrete walls below stands
  6- Previous leakage in some columns and wooden roof
  7- Cracks in block wall
  8- Cracks in tiles in toilets
  9- Cracks in screed flooring below stands

- For the swimming pool

  1- Previous leakage in roof slab soffit and stands soffit
  2- Dampness in concrete elements and block walls
  3- Damage and previous leakage in expansion joints
  4- Delamination of the concrete cover in ground slab, columns, beams, stands soffit and stairs below stands
  5- Cracks in block walls
  6- Cracks in concrete walls below stands, and cracks in stands
  7- Cracks between block wall and concrete elements

- For the Auditorium

  1- Cracks in slab soffit and ground beams
  2- Exposed corroded steel in slab soffit
  3- Previous leakage in slab soffit
  4- Delamination of the concrete cover in columns and ground beam
  5- Dampness in block walls and concrete elements
  6- Cracks in block walls
  7- Cracks between block walls and concrete elements

- **For the Auditorium**

Figure 4-1 Delamination of the concrete cover in column

Figure 4-2 Delamination of the concrete cover in column

Figure 4-3 Dampness and cracks in ground beam

Figure 4-4 previous leakage in column

Figure 4-5 Hollow sound during hammer testing which indicates defective concrete

Figure 4-6 Hollow sound during hammer testing which indicates defective concrete

Figure 4-7 Cracks in slab soffit

Figure 4-8 Cracks in slab soffit

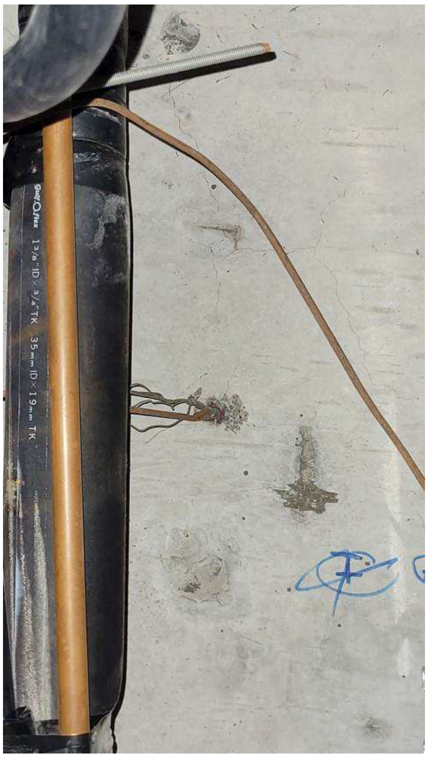

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Figure 4-11 Steel reinforcements exposure with corrosion in slab soffit

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Figure 4-25 Crack in block walls

Figure 4-26 Dampness in wooden roof

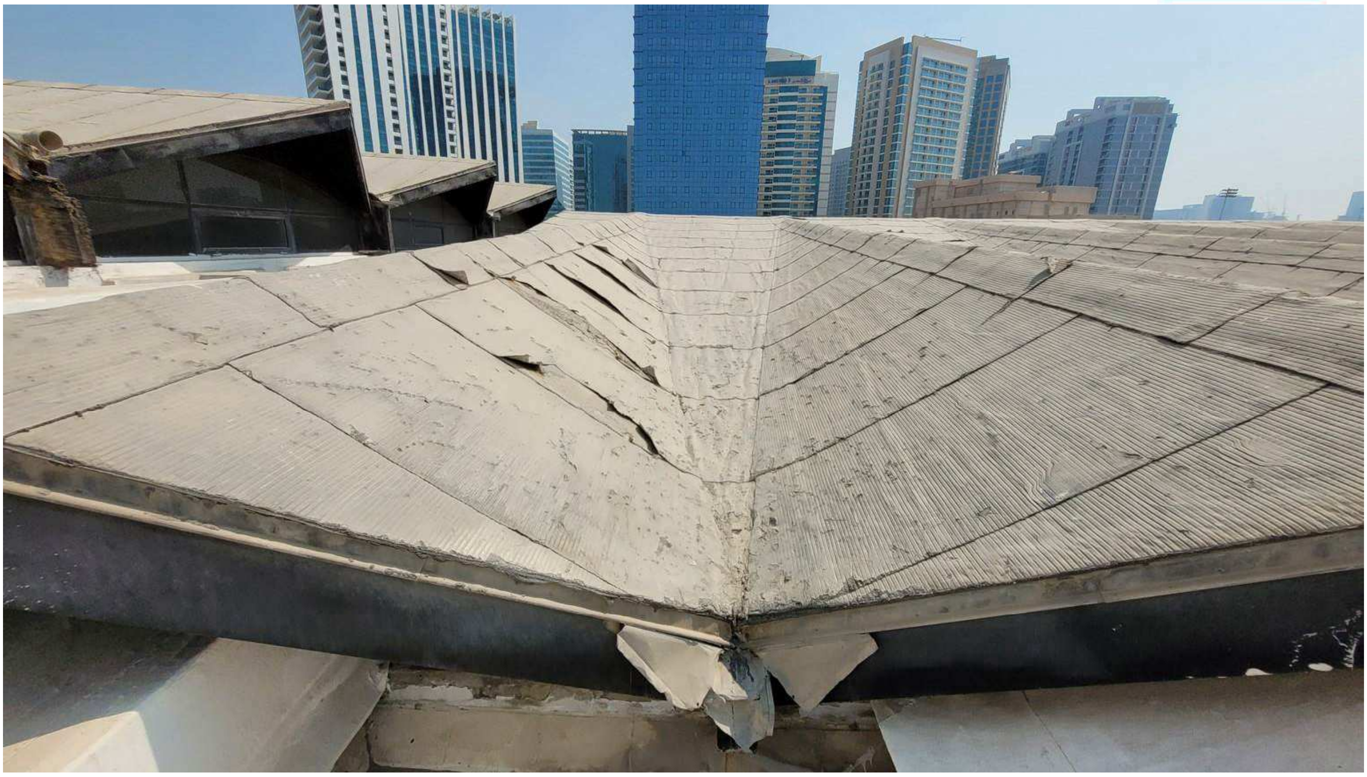

Figure 4-27 Dampness in wooden roof

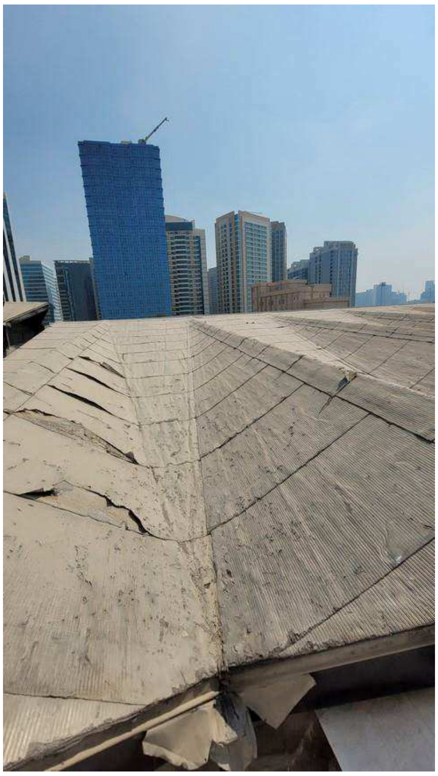

Figure 4-28 Dampness in wooden roof

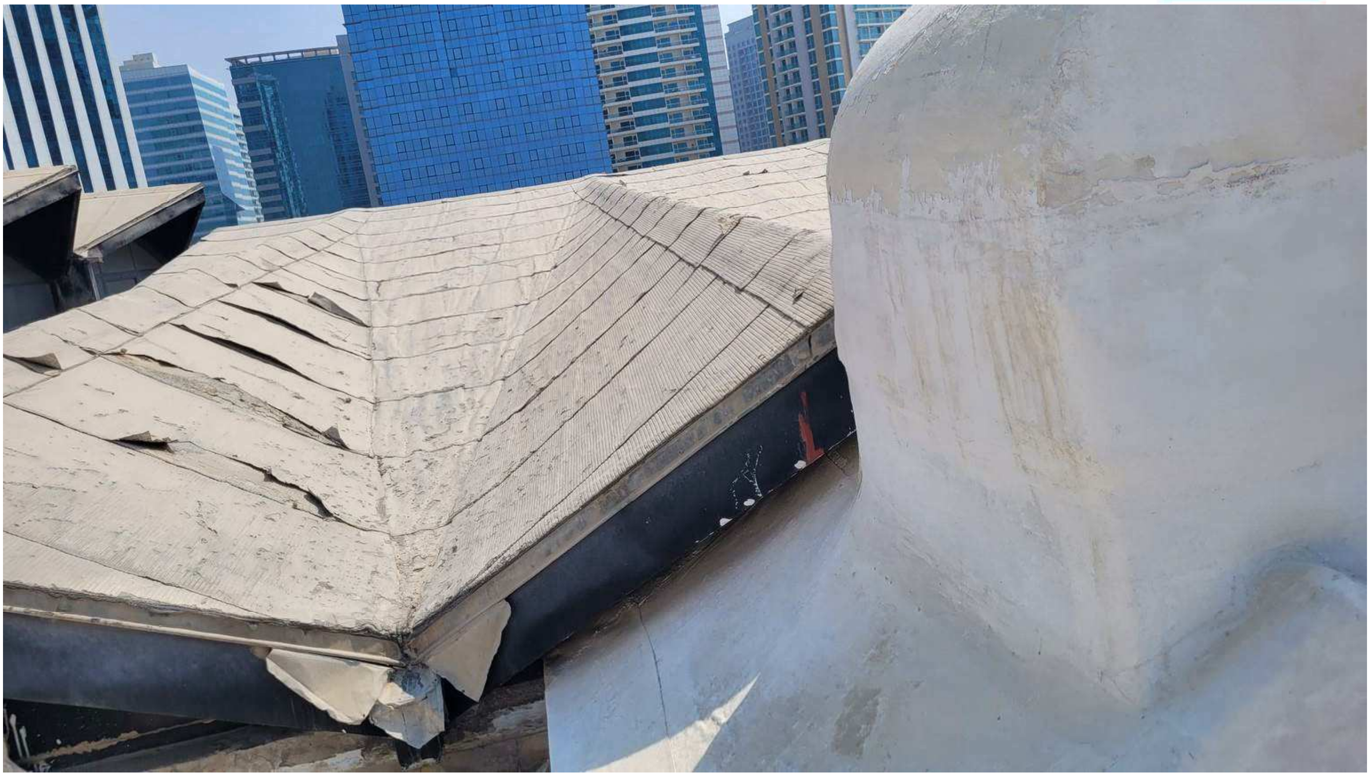

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Figure 4-30 Delamination of the concrete cover in roof beam

Figure 4-31 Crack in slab soffit

Figure 4-32 cracks in slab sofftt

Figure 4-33 Delamination of the concrete cover in column

Figure 4-34 Previous leakage in wooden roof

Figure 4-35 Cracks between block wall and concrete element

- **For the swimming pool and Gymnasium**

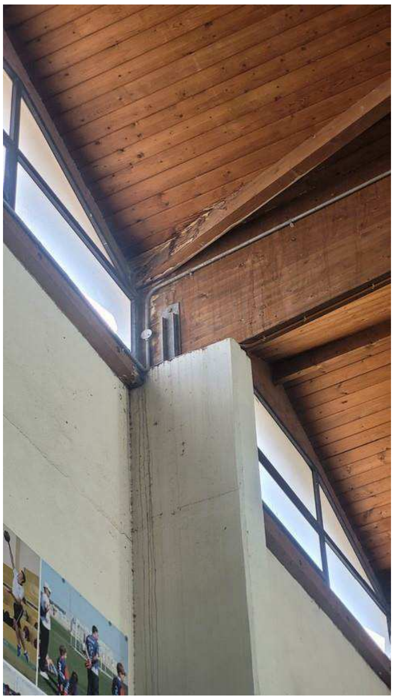

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Figure 4-38 Delamination of the concrete cover in column

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Figure 4-40 Dampness and cracks in block walls

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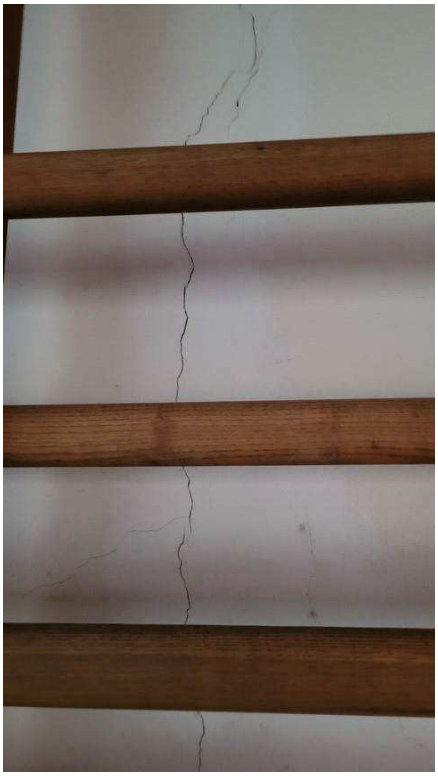

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Figure 4-46 Dampness and Delamination of the concrete cover in ground beam

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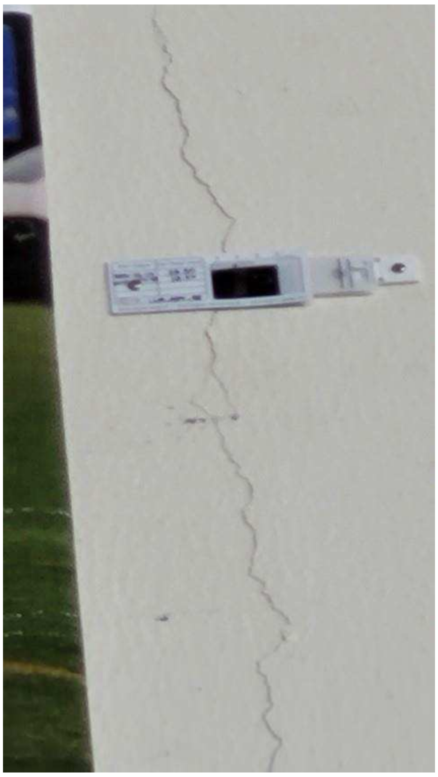

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Figure 4-56 Cracks in stands soffit

Figure 4-57 Cracks in the stand’s soffit

Figure 4-58 Delamination of the concrete cover and previous leakage in concrete wall

Figure 4-59 Delamination of the concrete cover and previous leakage in concrete wall

Figure 4-60 Cracks in concrete below stands

Figure 4-61 cracks in stands soffit

Figure 4-62 crack with previous leakage in stands soffit

Figure 4-63 Crack in stands soffit

Figure 4-64 Crack in concrete wall

Figure 4-65 Crack in stands soffit

Figure 4-66 Crack in stands soffit

Figure 4-67 Sign of previous leakage in slab soffit

Figure 4-68 Previous leakage in stands soffit

Figure 4-69 Cracks in stands soffit

Figure 4-70 Cracks in stands soffit

Figure 4-71 Cracks in stands soffit

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Figure 4-74 Sign of previous leakage in flooring

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Figure 4-86 Previous leakage in slab soffit

Figure 4-87 Previous leakage in slab soffit

Figure 4-88 Previous leakage in slab soffit

Figure 4-89 Previous leakage in slab soffit

Figure 4-90 Previous leakage in slab soffit

Figure 4-91 Previous leakage in wooden slab soffit

4.2 Concrete Cores

A total of 20 concrete cores (denoted as B1, G1, F1, …..) diameter of approximate 70 mm were taken from different locations in the buildings under consideration. A rotary core cutting machine with hollow diamond bits cooled with fresh water was used for coring (figures 4-92 and 4-93). Prior to drilling electromagnetic cover meter (Ground Penetrating Radar) was used to avoid cutting steel bars. Care was taken during coring to avoid as much as possible, causing any damage to the structural elements and cores.

All obtained cores were clearly marked, protected, put in container to avoid damage and were transferred from site to the laboratories for visual examination, photographing, cutting, trimming, determining of densities, and then testing for compressive strength. The physical and mechanical properties of the concrete were determined from the cores.

In general, medium grading and distribution of the aggregate were found in most of the cores. The detailed results from the cores are presented in figures 4-94.

The compressive strength tests were carried out according to the BS EN 12504 Part 1: 2009. The estimated in–situ cube strength varied between 18.5 and 27.3 N/mm^2 with an average of 22.2 N/mm^2.

Figure 4-92 During coring the foundation

Figure 4-93 During coring the column

Core No.	Core sampled from	Sampling Date	Length/ Diameter Ratio	Core Compressive Strength (N/mm²)	Correction Factor based on L/D ratio	Est. Insitu. Cylinder Strength (N/mm²)
1	GF Column CO1	07/08/2024	1.0	19.2	0.87	16.7
2	GF Column CO2		1.0	19.6	0.87	17.1
3	GF Column CO3		1.0	25.4	0.87	22.1
4	GF Column CO4		1.0	20.2	0.87	17.6
5	GF Column CO5		1.0	18.90	0.87	16.4
6	GF Column CO6		1.0	19.3	0.87	16.8
7	GF Column CO7		1.0	18.5	0.87	16.1
8	GF Column CO8		1.0	19.2	0.87	16.7
9	GF Column CO9		1.0	20.3	0.87	17.7
10	GF Column CO10		1.0	23.6	0.87	20.5
11	GF Column CO11		1.0	24.5	0.87	21.3
12	GF Column CO12		1.0	18.8	0.87	16.4
13	Foundation CO13	08/08/2024	1.0	25.3	0.87	22.0
14	Foundation CO14		1.0	27.2	0.87	23.7
1B	Basement 1B	07/08/2024	1.0	25.3	0.87	22.0
2B	Basement 2B		1.0	24.3	0.87	21.1
3B	Basement 3B		1.0	27.3	0.87	23.8
1F	1st Floor Column 1F	08/08/2024	1.0	20.5	0.87	17.8
2F	1st Floor Column 2F		1.0	21.3	0.87	18.5
3F	1st Floor Column 3F		1.0	25.4	0.87	22.1

Figure 4-94 The measured compressive strength results

1. **According to the ACI 214.4R-10 code:**

The procedures to determine an equivalent design strength for structural evaluation and analysis for the existing concrete elements to follow ACI 214.4R-10 "Guide for Obtaining Cores and Interpreting Compressive Strength Results".

9.1—Conversion of core strengths to equivalent in-place strengths

The in-place strength of the concrete at the location from which a core test specimen was extracted can be computed using the equation

$$f_c = F_{\ell/d} F_{dia} F_{mc} F_d f_{core} \qquad (9\text{-}1)$$

Table 9.1—Magnitude and accuracy of strength correction factors for converting core strengths into equivalent in-place strengths*

	Factor	Mean value	Coefficient of variation V, %
$F_{\ell/d}$: ℓ/d ratio†	Standard treatment‡:	$1-\{0.130-\alpha f_{core}\}\left(2-\frac{\ell}{d}\right)^2$	$2.5\left(2-\frac{\ell}{d}\right)^2$
	Soaked 48 hours in water:	$1-\{0.117-\alpha f_{core}\}\left(2-\frac{\ell}{d}\right)^2$	$2.5\left(2-\frac{\ell}{d}\right)^2$
	Dried§:	$1-\{0.144-\alpha f_{core}\}\left(2-\frac{\ell}{d}\right)^2$	$2.5\left(2-\frac{\ell}{d}\right)^2$
F_{dia}: core diameter	2 in. (50 mm)	1.06	11.8
	4 in. (100 mm)	1.00	0.0
	6 in. (150 mm)	0.98	1.8
F_{mc}: core moisture content	Standard treatment‡:	1.00	2.5
	Soaked 48 hours in water:	1.09	2.5
	Dried§:	0.96	2.5
F_d: damage due to drilling		1.06	2.5

*To obtain equivalent in-place concrete strength, multiply the measured core strength by appropriate factor(s) in accordance with Eq. (9-1).

†Constant α equals $3(10^{-6})$ 1/psi for f_{core} in psi, or $4.3(10^{-4})$ 1/MPa for f_{core} in MPa.

‡Standard treatment specified in ASTM C42/C42M.

§Dried in air at 60 to 70°F (16 to 21°C) and relative humidity less than 60% for 7 days.

Table 7 — Compressive strength classes for normal-weight and heavy-weight concrete

Compressive strength class	Minimum characteristic cylinder strength $f_{ck,cyl}$ N/mm²	Minimum characteristic cube strength $f_{ck,cube}$ N/mm²
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

- **As per the BS.EN 206 table for the average cube strength and comparing the f'c to obtain the Fcu value**

According to ACI 214.4R-10

No.	Location	Measured compressive strength (N/mm2)	l/d	$F_{(l/d)}$ (Table 9.1)	$F_{(dia.)}$ (Table 9.1)	F_{mc} (Table 9.1)	F_{damage} (Table 9.1)	f_{c}, in-place strength of concrete (Eq. 9.1) Mpa	fc_r fc mean (Eq. 9-2) Mpa	Characteristic Cylinder compressive strength F'c	Characteristic Cube Fcu
1B	Basement Floor Column	25.3	1.00	0.88	1.03	1.00	1.06	24.3	25	25	***31***
2B	Basement Floor Column	24.3	1.00	0.88	1.03	1.00	1.06	23.4			
3B	Basement Floor Column	27.3	1.00	0.88	1.03	1.00	1.06	26.3			
1G	Ground Floor Column	19.2	1.00	0.88	1.03	1.00	1.06	18.4	20	20	***25***
2G	Ground Floor Column	19.6	1.00	0.88	1.03	1.00	1.06	18.8			
3G	Ground Floor Column	25.4	1.00	0.88	1.03	1.00	1.06	24.4			
4G	Ground Floor Column	20.2	1.00	0.88	1.03	1.00	1.06	19.4			
5G	Ground Floor Column	18.9	1.00	0.88	1.03	1.00	1.06	18.1			
6G	Ground Floor Column	19.3	1.00	0.88	1.03	1.00	1.06	18.5			
7G	Ground Floor Column	18.5	1.00	0.88	1.03	1.00	1.06	17.7			
8G	Ground Floor Column	19.2	1.00	0.88	1.03	1.00	1.06	18.4			
9G	Ground Floor Column	20.3	1.00	0.88	1.03	1.00	1.06	19.5			
10G	Ground Floor Column	23.6	1.00	0.88	1.03	1.00	1.06	22.7			

11G	Ground Floor Column	24.5	1.00	0.88	1.03	1.00	1.06	23.6			
12G	Ground Floor Column	18.8	1.00	0.88	1.03	1.00	1.06	18.0			
13G	Foundation	25.3	1.00	0.88	1.03	1.00	1.06	24.3	25	25	***32***
14G	Foundation	27.2	1.00	0.88	1.03	1.00	1.06	26.2			
1F	First Floor Column	20.5	1.00	0.88	1.03	1.00	1.06	19.7	22	22	***27***
2F	First Floor Column	21.3	1.00	0.88	1.03	1.00	1.06	20.4			
3F	First Floor Column	25.4	1.00	0.88	1.03	1.00	1.06	24.4			

4.3 Cover Meter Surveys

Guidance on cover of reinforcement is given in the codes of practice. These have changed over the years, and it may be necessary to consult codes that were applicable at the time of construction, as well as current versions. Low cover is not necessarily a reason in itself for corrosion to occur. An assessment of the measured cover readings must be made in conjunction with the results of carbonation and chloride tests.

A concrete cover survey was conducted at selected areas on the concrete elements of the building to indicate the depth of reinforcement. The thickness of the concrete cover was measured by electromagnetic cover meter. The test results are presented in Table 4-1. The minimum and maximum values of the cover are 35 mm and 70 mm, respectively with an average concrete cover of 40 mm for the columns and 65 mm for the foundations. The concrete cover is higher than the carbonation depth in most cases as will be seen later in this investigation.

Table 4.1
Cover Meter Survey Test Results

Structural element	Location No.	Cover meter survey		
		Reading (mm)		Average reading (mm)
		Min.	Max.	
Basement Floor Column	B1	33	36	35
Basement Floor Column	B2	39	41	40
Basement Floor Column	B3	34	36	35
Ground Floor Column	G1	33	37	35
Ground Floor Column	G2	43	47	45
Ground Floor Column	G3	39	41	40
Ground Floor Column	G4	49	51	50
Ground Floor Column	G5	38	42	40
Ground Floor Column	G6	34	36	35
Ground Floor Column	G7	39	41	40
Ground Floor Column	G8	34	37	35
Ground Floor Column	G9	39	42	40
Ground Floor Column	G10	43	47	45
Ground Floor Column	G11	49	51	50
Ground Floor Column	G12	34	36	35
Foundation	G13	59	61	60
Foundation	G14	69	71	70
First Floor Column	F1	44	46	45
First Floor Column	F2	34	36	35
First Floor Column	F3	38	42	40

4.4 Depth of Carbonation

The intention behind the recommended cover in codes of practice is that carbonation should not reach the reinforcement within the design life of the element. Therefore, the average measured depths of carbonation with the knowledge of age of concrete can be used to determine the cause and rate of corrosion.

The depth of carbonation of concrete was measured on freshly exposed surface of concrete (by chipping the drilled hole used for dust sampling) and tested by applying a chemical indicator. The difference in alkalinity between carbonated and uncarbonated concrete is shown by a change in color. The indicator used is a solution of 1% phenolphthalein in diluted ethyl alcohol, which changes from colorless (transparent) to purple pink as the pH value rises above 10. Consequently, the outer, carbonated layer of concrete retains its natural color while uncarbonated concrete is stained pink. This test applies only to freshly exposed surfaces, because reaction with atmospheric carbon dioxide starts immediately. It is also assumed that the tested surface is not contaminated with dust from uncarbonated concrete. Figure 4-94 shows the process of testing the carbonation depth. Table 4-2 shows the carbonation depth of the tested locations.

Figure 4-94 During the carbonation testing

Table 4.2
Carbonation Results

Structural element	Location No.	Carbonation (mm)	Average cover (mm)	Protected or not
Basement Floor Column	B1	9	35	Yes
Basement Floor Column	B2	10	40	Yes
Basement Floor Column	B3	10	35	Yes
Ground Floor Column	G1	8	35	Yes
Ground Floor Column	G2	10	45	Yes
Ground Floor Column	G3	10	40	Yes
Ground Floor Column	G4	15	50	Yes
Ground Floor Column	G5	11	40	Yes
Ground Floor Column	G6	10	35	Yes
Ground Floor Column	G7	8	40	Yes
Ground Floor Column	G8	9	35	Yes
Ground Floor Column	G9	10	40	Yes
Ground Floor Column	G10	10	45	Yes
Ground Floor Column	G11	15	50	Yes
Ground Floor Column	G12	9	35	Yes
Foundation	G13	10	60	Yes

Foundation	G14	11	70	Yes
First Floor Column	F1	12	45	Yes
First Floor Column	F2	10	35	Yes
First Floor Column	F3	11	40	Yes

The test results showed that the depth of carbonation is lower than the concrete cover in all of the tested locations, which is an indication that the reinforcing steel is under low risk of corrosion due to carbonation infiltration.

4.5 Chloride Content in Dust Samples

Dust samples were taken from twenty (20) locations by the working team. These dust samples were taken to determine the chloride contents.

The chloride content is critical to the life of the reinforcement. The risk that the reinforcement will rust as a result of chloride contamination depends on:

- the concentration of the chloride in the concrete
- the alkalinity of the concrete
- type of cement
- presence of chloride at the time of mixing
- penetration of chloride through the hardened concrete surface from aggressive atmosphere

Current concrete specifications, including the CIRIA "Guide to the Construction of Reinforced Concrete in the Arabian Peninsula, 2002", call for a maximum chloride content Presented in Table 4.4.

Table 4.3
Maximum chloride content according to CIRIA 2002

Type of concrete	***Max. Chloride ions (Cl^-) Content*** *(% by Weight of Cement)*
Reinforced concrete made with Portland cements containing less than about 4% C_3A (e.g. sulphate-resisting Portland cement)	*0.15*
Reinforced concrete made with Portland cements containing 4% or more C_3A (OPC and ASTM types I and II usually contain more than 4% C_3A)	*0.30*
Unreinforced concrete	*0.60*

* The chloride contents by weight of cement were calculated using the average cement content and as received concrete density of the core specimens obtained from each location

The chloride content of each increment of the concrete dust samples was determined according to BS 1881: Part 124:1988. The chloride content by total weight of the concrete, expressed as chloride ions in all the tested elements varied between 0.01% and 0.33% and the chloride ion by weight of cement varied between 0.06% and 1.98%. The results are presented in Table 4-4.

The chloride content in the concrete of the tested reinforced concrete elements under consideration was found to be higher than the limits in most of the tested locations indicating a high corrosion risk due to Chloride infiltration.

Table 4.4
Samples of Chloride Content

Test No.	Depth (mm)	Chloride Content as Cl^- % by Wt. of	
		Concrete	* Cement
B1	0-25	0.02	0.12
	25-50	0.02	0.12
	50-75	0.01	0.06
B2	0-25	0.07	0.42
	25-50	0.06	0.36
	50-75	0.06	0.36
B3	0-25	0.16	0.96
	25-50	0.14	0.84
	50-75	0.11	0.66
G1	0-25	0.07	0.42
	25-50	0.06	0.36
	50-75	0.05	0.30
G2	0-25	0.08	0.48
	25-50	0.06	0.36
	50-75	0.05	0.30
G3	0-25	0.08	0.48
	25-50	0.06	0.36
	50-75	0.06	0.36
G4	0-25	0.09	0.54
	25-50	0.07	0.42
	50-75	0.06	0.36
G5	0-25	0.09	0.54
	25-50	0.07	0.42
	50-75	0.06	0.36
G6	0-25	0.06	0.36
	25-50	0.04	0.24
	50-75	0.04	0.24
G7	0-25	0.07	0.42
	25-50	0.06	0.36
	50-75	0.04	0.24
G8	0-25	0.07	0.42
	25-50	0.06	0.36
	50-75	0.04	0.24
G9	0-25	0.02	0.12
	25-50	0.01	0.06
	50-75	0.01	0.06
G10	0-25	0.01	0.06
	25-50	0.01	0.06

	50-75	0.01	0.06
G11	0-25	0.01	0.06
	25-50	0.01	0.06
	50-75	0.01	0.06
G12	0-25	0.03	0.18
	25-50	0.02	0.12
	50-75	0.02	0.12
G13	0-25	0.09	0.54
	25-50	0.08	0.48
	50-75	0.07	0.42
G14	0-25	0.09	0.54
	25-50	0.07	0.42
	50-75	0.07	0.42
F1	0-25	0.07	0.42
	25-50	0.06	0.36
	50-75	0.04	0.24
F2	0-25	0.33	1.98
	25-50	0.30	1.80
	50-75	0.28	1.68
F3	0-25	0.31	1.86
	25-50	0.28	1.68
	50-75	0.26	1.56

* The chloride contents by weight of cement were calculated using the average cement content and as received concrete density of the core specimens obtained from each location.

4.6 Electro Half Cell Potential Measurements Tests

Corrosion is an electrochemical process and it is possible to obtain an indication of whether the reinforcement in concrete is in a stage where it could corrode using electro potential mapping, even where there are no visible symptoms of distress.

The state of reinforcement in the structures can be obtained by measuring electrical potentials by means of standard half-cells, provided that the reinforcement is electrically continuous. One terminal of high impedance milli-voltmeter can be connected to a point on the reinforcement and the other terminal to a half-cell or copper/copper sulphate or silver/silver chloride which is placed in contact with the surface of the concrete. The half-cell, in practice, consists usually of a copper electrode immersed in an electrotype of copper sulphate solution (Figures 4-95 and 4-96).

Figure 4-95 Canin system for measuring the potential

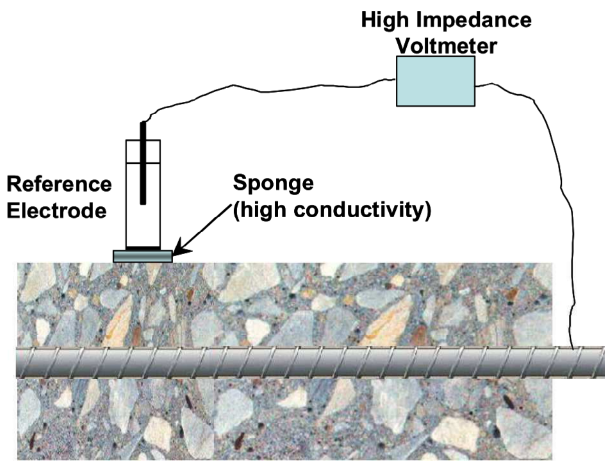

Figure 4-96 Schematic diagram for half-cell potential measurement

The tube containing the electrolyte is closed by a permeable pad saturated with the electrolyte or other conductive liquid, and this is placed in contact with the surface of concrete. By moving the half-cell on the member under examination it is possible to draw equipotential contours. Areas showing potentials more negative than -350 mV relative to copper/copper sulphate electrode (CSE) are generally considered to be those in which the steel is anoxic and no longer passive, so it may be actively corroding.

Corrosion is likely to be negligible in areas showing potentials less than -200mV. However, different investigators have assigned different values to these criteria, and at intermediate potentials the state will be uncertain.

The equipotential contours will also show areas, which although still passive at present, may develop active anodes, later. The general pattern of equipotential contours provided useful information to an experience observer, and it will often be of more use than absolute values of potential. It is important to realize that, while potential measurements may show where steel is no longer passive, they do not show the rate of corrosion.

Initially, a segment of the reinforced network of the concrete member is located and uncovered. At grid points where the sensor had to make contact with the concrete, the paint was scraped off. The reading was made with a Half cell corrosion test meter in accordance to ASTM C 876-91.

From the grid reading equipotential contours, which were drawn at intervals of 50mV:

- If potentials over an area are numerically less than **-200mV/CSE**, then there is more than 90% probability that no reinforcement steel corrosion is occurring in that area at the time of measurement.
- If potentials over an area are in the range of **–200 to -350 mV/CSE**, corrosion activity of the reinforcing steel in that area is uncertain.
- If potential over an area are numerically more than **-350 mV/CSE** there is more than 90% probability that reinforcing steel corrosion is occurring in that area at the time of measurements.
- Positive readings, if obtained, generally indicated insufficient moisture in the concrete and were not considered. Further wetting continued.

Electro Half-cell Potential Survey was conducted at twenty (20) concrete surfaces locations. The survey consisted of conducting grid measurements at the selected area. The readings were taken at spacing of 100 mm.

The summary of the electro half-cell potential survey is presented in table 4-5. The table presents the number, the range and the percentage distribution of measurements for each surveyed element. Since the readings are taken on a square grid of known interval for each element, the percentages of readings also represent the distribution of areas with more than 90% probability or no corrosion, and with uncertain corrosion.

Figure 4-97 During conducting the half-cell potential test

Table 4-5
Electro Half – Cell Potential Survey Results

Half – Cell Potential Measurement						
Test No.	Values mV		% Measurements			No. of Readings
	Minimum Reading	Maximum Reading	< - 200mV	-200 to −350mV	> -350mV	
B1	-110	-208	90	10	0	9
B2	-480	-521	0	0	100	9
B3	-206	-257	0	100	0	9
G1	-98	-172	100	0	0	9
G2	-142	-180	100	0	0	9
G3	-127	-150	100	0	0	9
G4	-302	-422	0	20	80	9
G5	-80	-290	20	80	0	9
G6	-140	-169	100	0	0	9

G7	-240	-265	0	100	0	9
G8	-139	-171	100	0	0	9
G9	-138	-182	100	0	0	9
G10	-99	-164	100	0	0	9
G11	-112	-181	100	0	0	9
G12	-93	-115	100	0	0	9
G13	-235	-250	0	100	0	9
G14	-210	-288	0	100	0	9
F1	-259	-302	0	100	0	9
F2	-116	-174	100	0	0	9
F3	-220	-275	0	100	0	9
	Significance (ASTM C876-91)		> 90% Probability of no Corrosion	Corrosion Uncertain	> 90% Probability of Corrosion	-

The Half-cell potential tests showed an uncertain probability of corrosion and a high probability of no corrosion occurring at the time of testing for most of the tested locations. However, test location No's. B2 & G4 showed a high probability of corrosion occurring at the time of testing.

4.7 Electrical Resistivity Measurements of Concrete Surface

The corrosion of steel in concrete is an electro-chemical process which creates a current flow causing metal to dissolve so that it is possible to assess the probability of reinforcement corrosion by evaluating the electrical resistance of the concrete. Electrical current is passed through the outer probes & the potential drop is measured by the inner probes. From the current & voltage drop measurements, the resistivity of concrete can be measured. This resistivity can be related to quality of concrete.

Surface resistivity measurement provides extremely useful information about the state of a concrete structure. Not only has it been proven to be directly linked to the likelihood of corrosion and the corrosion rate, recent studies have shown that there is a direct correlation between resistivity and chloride diffusion rate. The versatility of the method can be seen in these example applications:

- Indication of corrosion rate
- Correlation to chloride permeability
- On site assessment of curing efficiency
- Determination of zonal requirements for cathodic protection systems
- Identification of wet and dry areas in a concrete structure

- Indication of variations in the water/cement ratios within a concrete structure
- Identification of areas within a structure most susceptible to chloride penetration
- Correlation to water permeability of rock

The Concrete Resistivity Meter (Figure 4-98) replaced the Rapid Chloride Permeability Test and Surface Resistivity for ASTM C1202 and AASHTO T277.

Figure 4-98 The concrete Resistivity Meter

The Surface Resistivity (SR) test is a much quicker and easier test for estimating concrete permeability. It is a proven and mature test method which can replace the more laborious rapid chloride permeability test. The State of Louisiana has designated this test method as LATR 233.

A current is applied to the two outer probes and the potential difference is measured between the two inner probes. The current is carried by ions in the pore liquid (Figure 4-99). The calculated resistivity depends on the spacing of the probes.

Resistivity $\rho = 2\pi aV/I$ [kΩcm]

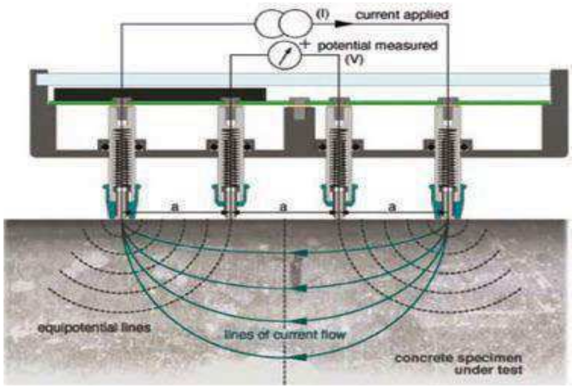

Figure 4-99 Concept of concrete resistivity

The interpretation of resistivity measurements is given in Table 4-6 which can be used to determine the likelihood of corrosion.

Table 4.6
Likelihood of corrosion as function of the concrete resistivity

No.	Concrete resistivity	Interpretation on Corrosion
1	$\rho \geq 100$ kΩcm	corrosion is unlikely - Low corrosion rate
2	ρ = 50 to 100 kΩcm	risk of corrosion is low - Low to moderate corrosion rate
3	ρ = 10 to 50 kΩcm	risk of corrosion is moderate - High corrosion rate
4	$\rho \leq 10$ kΩcm	risk of corrosion is high - Very high corrosion rate

The test results of twenty (20) locations are shown in Table 4-7.

Table 4.7
Concrete resistivity

Structural Element	Location No.	Resistivity (kΩcm)
Basement Floor Column	B1	1212
Basement Floor Column	B2	2.3
Basement Floor Column	B3	381
Ground Floor Column	G1	30.9
Ground Floor Column	G2	93
Ground Floor Column	G3	183.5
Ground Floor Column	G4	11.1
Ground Floor Column	G5	187.2
Ground Floor Column	G6	110.5
Ground Floor Column	G7	32.3
Ground Floor Column	G8	90.5
Ground Floor Column	G9	142.7
Ground Floor Column	G10	130.7
Ground Floor Column	G11	1.6
Ground Floor Column	G12	106.3
Foundation	G13	12.7
Foundation	G14	11.5
First Floor Column	F1	77.4
First Floor Column	F2	83.2
First Floor Column	F3	225

The resistivity tests showed a low and low to moderate corrosion rates for most of the tested locations. Except for test location No.'s G1, G4, G13 & G14 which showed a high corrosion rate and test location No.'s B2 & G11 which showed a very high corrosion rate.

Figure 4-100 During measuring the resistivity

4.8 Ultrasonic Pulse Velocity

According to BS EN 12504-4:2004: Determination of ultrasonic pulse velocity, the principle of ultrasonic pulse velocity tests can be summarized as follows:

A pulse of longitudinal vibrations is produced by an electro-acoustical transducer held in contact with one surface of the concrete under test. After traversing a known path length in the concrete, the pulse of vibrations is converted into an electrical signal by a second transducer and electronic timing circuits enable the transit time of the pulse to be measures. Ultrasonic pulse velocity tests are used to verify the quality of concrete. Generally concrete with pulse velocity greater than 4000m/s is considered to be of good quality. Table 4-8 shows the velocity criterion for concrete quality grading for direct transmission, table 4-9 for in-direct transmission.

Table 4.8
Velocity Criterion for Concrete Quality Grading (Direct)

No.	Pulse Velocity in core probing (m/sec.)	Concrete Quality Grading
1	Above 4500	Excellent
2	3500 to 4500	Good
3	3000 to 3500	Medium
4	2000 to 3000	Poor
5	Less than 2000	Very poor

Table 4.9
Velocity Criterion for Concrete Quality Grading (in-direct)

No.	Pulse Velocity in core probing (m/sec.)	Concrete Quality Grading
1	Above 4000	Excellent
2	3000 to 4000	Good
3	2500 to 3000	Medium
4	1500 to 2500	Poor
5	Less than 1500	Very poor

The test results of twenty (20) tests at different locations are presented in Table 4-10 (Figures 4-101 and 4-102). The ultrasonic pulse velocity of the existing concrete ranged between 256 to 5682 m/s on average 1847 m/s which is lower than 2500 m/s. In general, the concrete quality is poor to very poor.

Figure 4-101 During measuring the Ultrasonic Pulse Velocity –Indirect

Figure 4-102 During measuring the Ultrasonic Pulse Velocity –Indirect

Table 4.10
Summary of the Ultrasonic Pulse Velocity tests

Structural Element	Location No.	Ultrasonic pulse velocity (m/sec.)
Basement Floor Column	B1	1832
Basement Floor Column	B2	1370
Basement Floor Column	B3	3953
Ground Floor Column	G1	324
Ground Floor Column	G2	1403
Ground Floor Column	G3	1727
Ground Floor Column	G4	256
Ground Floor Column	G5	2294
Ground Floor Column	G6	1838
Ground Floor Column	G7	1095
Ground Floor Column	G8	746
Ground Floor Column	G9	1256
Ground Floor Column	G10	4065
Ground Floor Column	G11	5682
Ground Floor Column	G12	1345
Foundation	G13	779
Foundation	G14	1420
First Floor Column	F1	631
First Floor Column	F2	1100
First Floor Column	F3	3831

5 INTERPRETATION OF TEST RESULTS

- The cores tests of the ground floor columns indicated that the design concrete characteristic strength (f_{cu}) is equal to 31 N/mm^2, 25 N/mm^2, 32 N/mm^2, & 27 N/mm^2 foe the basement columns, ground floor columns, foundations & first floor columns respectively.
- The minimum and maximum values of the cover are 35 mm and 70 mm, respectively with average concrete cover of 40 mm for the columns and 65 mm for the foundations
- The depth of carbonation is lower than the concrete cover in all of the tested cases which is an indication that the steel reinforcement is under a lowe risk of corrosion due to carbonation infiltration.
- The chloride content in the concrete of the tested reinforced concrete elements under consideration was found to be higher than the limits in most of the tested locations indicating a high corrosion risk due to Chloride infiltration.
- The Half-cell potential tests showed an uncertain probability of corrosion and a high probability of no corrosion occurring at the time of testing for most of the tested locations. However, test location No's. B2 & G4 showed a high probability of corrosion occurring at the time of testing.
- The resistivity tests showed a low and low to moderate corrosion rates for most of the tested locations. Except for test location No.'s G1, G4, G13 & G14 which showed a high corrosion rate and test location No.'s B2 & G11 which showed a very high corrosion rate.
- The concrete quality at the concrete elements is very poor to poor.

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