Engineering Journal of Qatar University, Vol. 7, 1994, p. 201 - 229

CONCRETE DETERIORATION AND REPAIR IN AN INDUSTRIAL ENVIRONMENT

Mustafa H. El-Kady
Senior Engineer, Maintenance General Services
Qatar Petrochemical Company, Umm-Said, Qatar.

M.A. Abdul-Salam
Professor, Civil Engineering Department
Qatar University, Doha, Qatar.

ABSTRACT

This case study is concerned with concrete deterioration and its repair in an Industrial Plant (Qatar Petrochemical Company). Three different cases are identified according to the type and the environment of the structural members. For each case, the following is covered: history of the deteriorated concrete member, investigation done, analysis of the phenomena, the method used to repair the deteriorated structure, and its condition few years after repair.

INTRODUCTION

Reinforced concrete is a widely used material in the world. It finds almost universal application in construction from single story buildings to sky scrapers, and from road works to bridges, dams, sea defense walls, and many types of industrial structures .

Concrete is a very economical building material as 80-90 % of its content are usually available at moderate cost. It hardens with age and the process of hardening continues for a long time after the concrete has attained sufficient strength.

Reinforced concrete has numerous specific applications in an industry such as :

1- **Foundations and bases for ;**
   a) Process Equipment (Heat Exchangers, Columns Drums, Tanks, Boilers., Pipe Racks Supports, etc.).
   b) Rotary Machinery (Steam and Gas Turbines, Air and Gas Compressors, Centrifugal Pumps .etc.).
   c) Reciprocating Machinery (Diesel Engines, Reciprocating Air & Gas Compressors, Reciprocating Pumps etc.).
   d) Work Shop Machinery (Lathes , Milling Machine, Drilling machines, Presses, etc.).

2- **Special Construction Units;**
   a) Under Ground Sulfur Pits.
   b) Sea Water Intake Station.
   c) Sea Water Out-fall Chamber.

3- **Structural Frame Systems .**

However, many structures constructed in the Arabian Gulf area have deteriorated and show signs of failure within few years after construction. Such deterioration or failure may lead to losses in the plant income due to stoppage or shutdown in the production process.

In this paper, the deterioration of structural concrete and the methods of repair are described for some cases in Qatar Petrochemical Company (hereafter called QAPCO). The investigation and analysis done to identify the causes of failure or deterioration and condition of the repaired structures after some years of repair are also included.

Initial survey of concrete condition in the plant complex resulted in identifying three cases of deterioration which are discussed herein.

CASE 1: DETERIORATION AND REPAIR OF CONCRETE SUPPORTS OF STEEL PIPE RACKS

Figures (1) and (2) show a general view of the pipe rack with the concrete support. Each of these concrete supports is a separate concrete construction which consists of a footing and a short column partly embedded in the ground with 500 mm length of the column exposed above the ground surface.

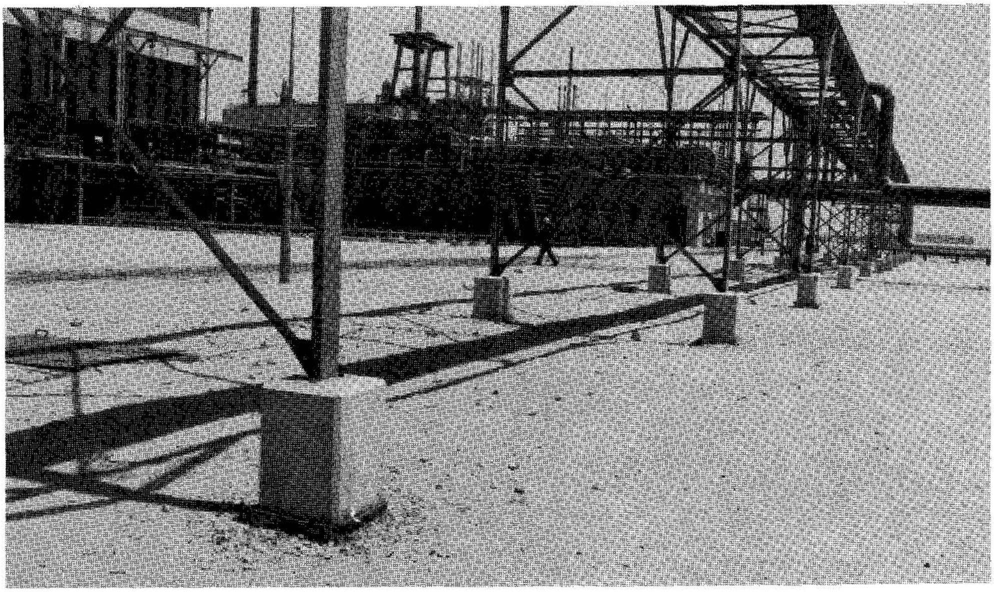


Fig. 1: General view of a pipe rack and its concrete supports

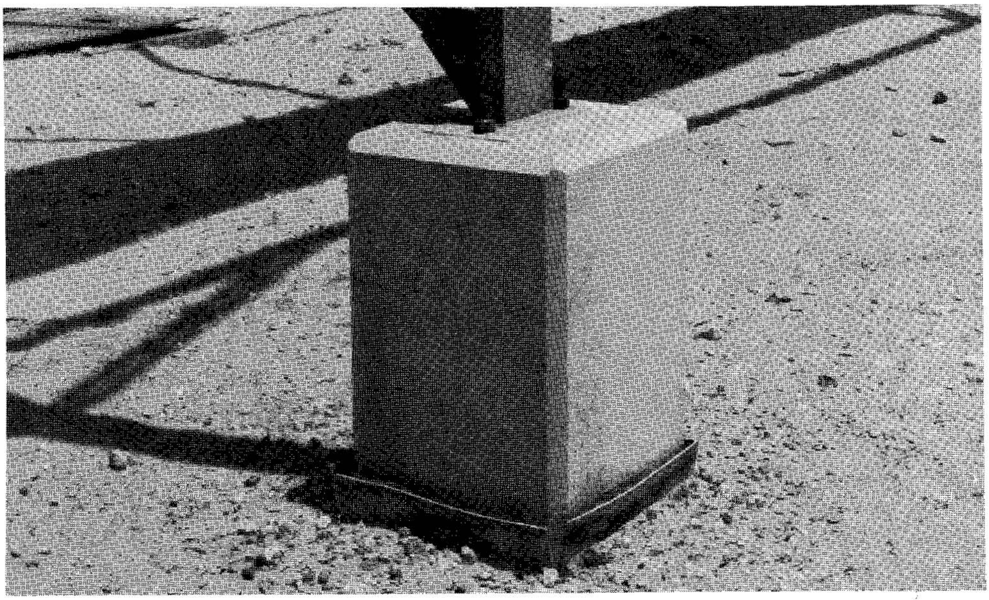


Fig. 2: Single concrete support for a pipe rack

These concrete supports are designed to bear the dead load of the pipe lines, the steel structure of the pipe racks , the lateral loads created by expansion (during heating up) or contraction (during the cooling down) of the pipe lines and due to the wind pressure.

The concrete supports were constructed in 1978/1979 using sulfate resistant cement. After few years, severe cracks were observed in the column above the ground surface.

Visual inspection (without sampling or laboratory analysis) was done by excavating and exposing completely the column and the footing of some of these concrete supports. The inspection led to the following results ;

a) Some supports (Fig. 3) had completely deteriorated and the footing and the column had deep cracks. Most re-bars were severely corroded and some of them completely diminished in size.
b) Other supports (Fig. 4) had developed cracks in the upper portion above ground and for a distance of 300-400 mm underneath the ground surface.
c) All concrete surfaces were bare without any surface coating or protection .
d) The concrete cover was no more than 25 mm.

By analyzing the observed patterns of cracking it was concluded that the main causes for deterioration are :

1- Sea salt (chloride) penetration from soil.
2- Sea salt (chloride) penetration by capillary action.
3- Sun exposure.

Sea salt (chloride) penetration from soil

The soil at QAPCO`s site is a hydraulic back fill , consisting of dredged material from the sea bottom .As a result , the soil is saturated with sea salt which is mostly in the form of chloride.

As the concrete supports are constructed with ordinary concrete of sulfate resistant cement without any coating and with small concrete cover, chloride penetrated through pores and shrinkage hair cracks appeared in the concrete. Consequently, the re-bars got corroded which led to the expansion, hence more

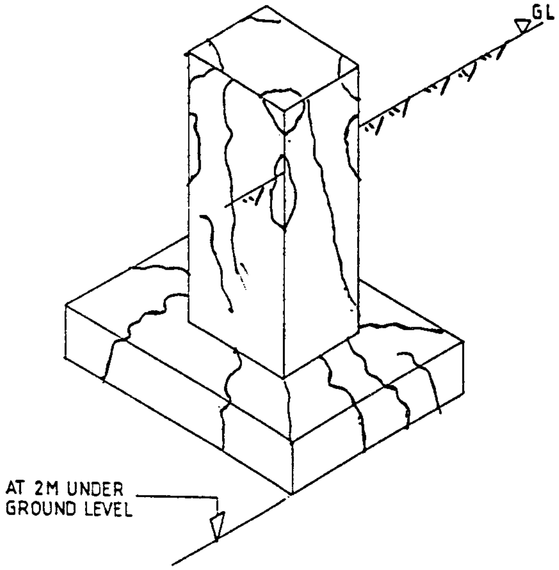


Fig. 3: Complete deterioration of concrete support

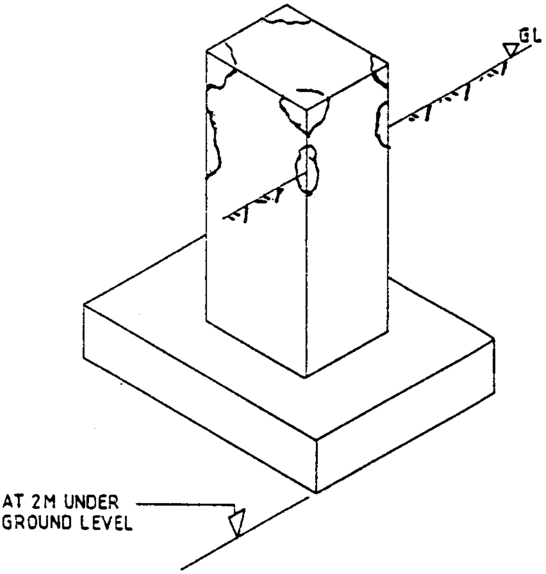


Fig. 4: Partial deterioration of concrete support

cracks and more penetration of the chloride and so on until complete deterioration and failure of the supports (Fig. 5).

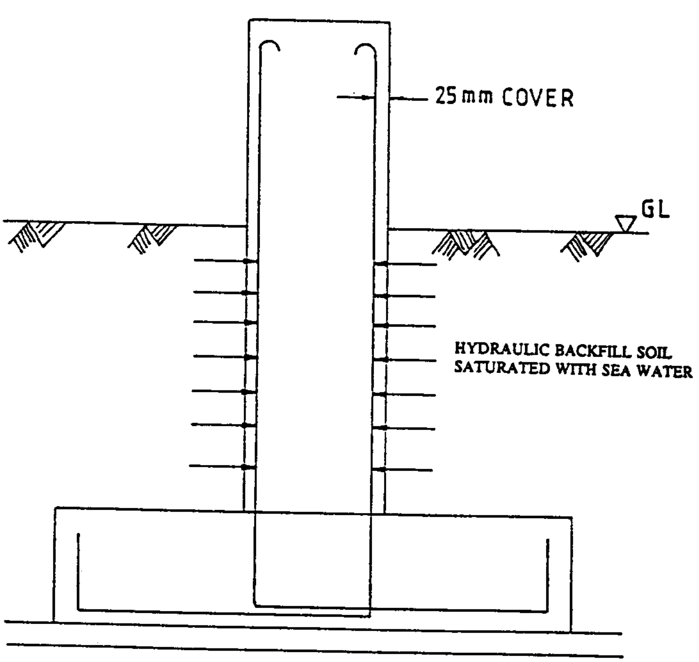


Fig. 5: **Penetration of salt into R.C.C.**

Sea salt (chloride) penetration by capillary action

The water table at the site is about 2 m below ground level and therefore most bases of the footings of the concrete supports are in contact with the under ground sea water . As the concrete has smaller pores than the adjacent ground soil the sea water rises through the concrete to a higher level than through the soil due to the capillary action. In many of supports the sea water reached the ground level and evaporated leaving the salt (chloride) inside the top portion of the support. The process is a continuos one, which means the salt is pumped to the top portion of the concrete support. This accumulated salt reacted with both the concrete and the re-bars and led to the deterioration of the top portion of the concrete supports (Fig. 6).

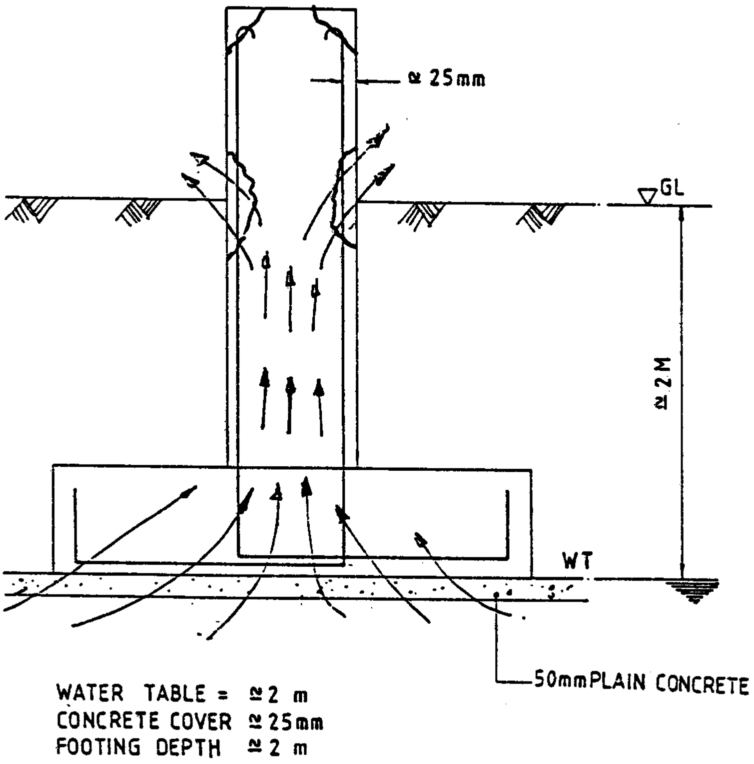


Fig. 6: Under ground salt pumping

Exposure to Sun

Exposure of concrete to sun causes the following:

1. Expansion-Contraction process, which might lead to numerous cracks due to temperature variations (from 30°C during night to about 80° C at noon in summer time, measured at the surface of the concrete within the same day, and from a minimum of 5°C during winter to a maximum of 80°C during summer).
2. Speeds up all harmful chemical reactions between chloride and both the cement of the concrete and the re-bars.
3. Speeds up the above mentioned salt immigration and salt pumping phenomena.

As a conclusion of the above mentioned investigation and analysis, it was clear that to improve the resistance of concrete to harmful environment and to extend its service life, remedial action will not be sufficient and repair should be done by a new concrete of better properties than the existing one.

Necessary investigation was made to find the suitable type of cement, the right concrete mix and the adequate coating systems for protecting both the under ground and the above ground parts. The folowing was found:

1. Sulfate resistant cement has higher permeability towards chloride ions than the Ordinary Portland cement (with lower C_3A).
2. Water Cement Ratio has significant effect on the permeability of concrete (the higher the water/cement ratio the higher the shrinkage i.e. more setting cracks).
3. "Micro silica" is an extremely reactive pozzolan, it will combine with the concrete to form calcium-silicate hydrates (CSH). This leads to an increased formation of binding agents and the concrete will show increased properties of resistance against chlorides.

Therefore, the deteriorated supports were refurbished using concrete of the new mix design in the following ways:

A- The completely deteriorated supports were completely demolished and reconstructed with the following concrete mix design, (figure 7):

1- Cement : Ordinary Portland Cement.
2- Minimum cement content of 400 kg / m^3 of concrete.
3- 10-15 % of cement to be replaced by Micro Silica.
4- Maximum water/cement ratio 0.4 .
5- Maximum total content of chloride from all sources not to exceed 0.3% by weight of cement.
6- Maximum total content of sulfates from all sources not to exceed 4% by weight of cement.
7- Minimum cube strength after 28 days not to be less than 30 N/mm^2 .
8- Maximum temperature for concrete pouring 25°C .
9- All under ground concrete surfaces coated by coal tar epoxy of minimum dry film thickness of 125 micron.
10- All above ground surfaces coated by epoxy sealant as a primer and high built epoxy paint of minimum dry film thickness of 1000 micron .
11- The excavated areas around the concrete supports back-filled with salt free desert fill of about 1 m thickness.

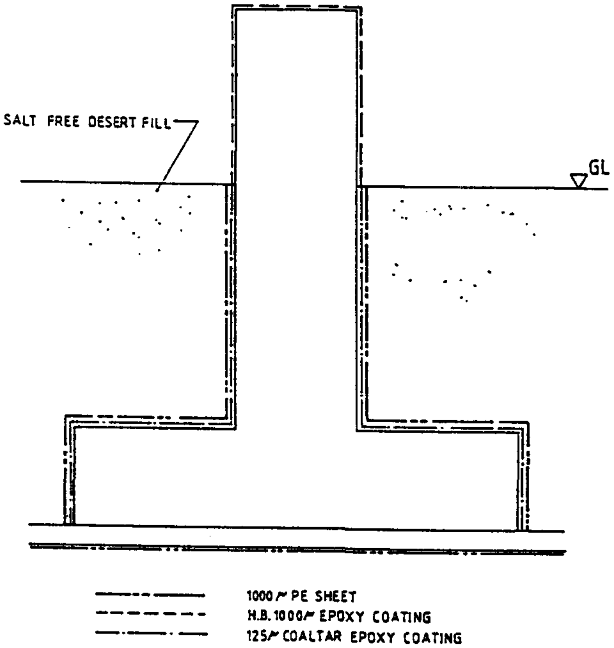


Fig. 7: **Reconstructed foundation with improved specification**

B- The partially deteriorated supports got patch repair according to the following procedure:

1- The cracked loose concrete was broken to expose the sound one. The breaking out continued to expose the full circumference of the steel bars and to a further depth of 50 mm beyond it .

2- The corroded bars of diameter less than 0.7 of the original diameter were replaced.

3- All exposed reinforcing bars and other steel structure parts in contact with the concrete were grit blasted up to sa 2.5 according to the Swedish Standard Institution specification for surface preparation for painting steel surfaces (SIS 055900 - 1967) or ISO 8501-1-1988, [1].

4- The grit blasted steel parts were coated with "Epoxy Zinc Rich Primer".

5- The under ground and the above ground concrete parts were coated with the same system described above for reconstructing the completely deteriorated supports.

6- The back filling was done by salt free desert fill of about 1 m thickness.

These two procedures were used in the year 1987 to repair about 300 pipe rack supports . Figure-1 and Figure-2 show the conditions of these supports after 5 years of repair, the supports still look like new ones. Further check was carried out in 1994 using non- destructive methods and proved that the concrete condition is sound. The results of this testing are presented later in this paper.

In the year 1991 the same procedures were used to repair concrete supports for "High Pressure Pipe Lines" in which the gas is compressed to 2000 bar by the reciprocating compressor (Fig. 8), and the concrete base of the deethanizer C1501 (Fig. 9). All figures indicate that even after two years of repair the concrete is in good condition .

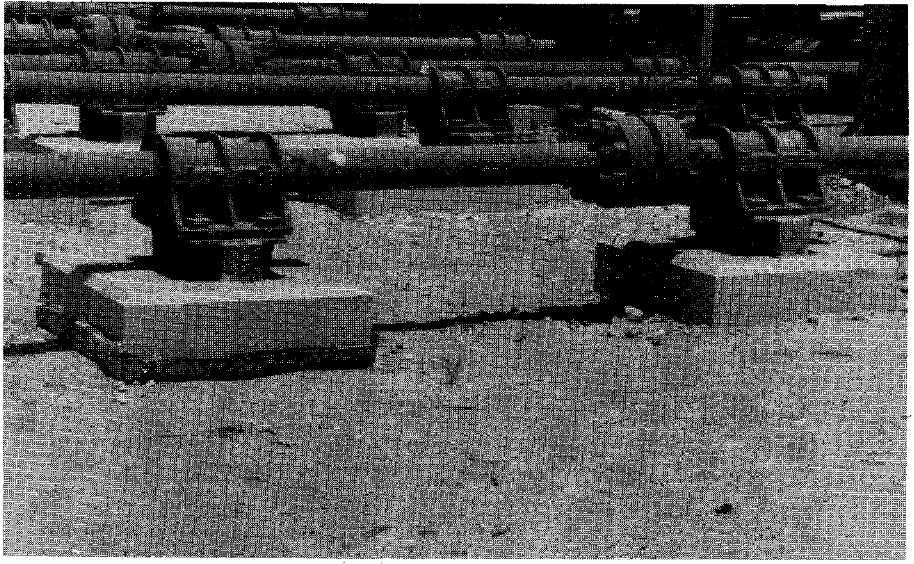


Fig. 8: Close-up view of high pressure pipe supports

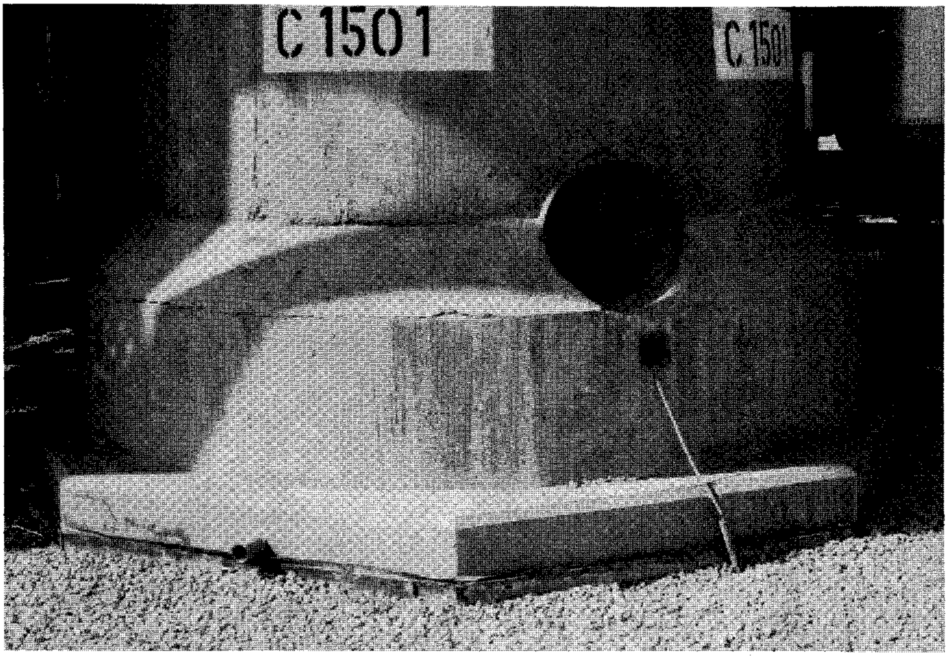


Fig. 9: **Concrete base of column C-1501 after repair**

CASE 2: DETERIORATION AND REPAIR OF SEA WATER INTAKE STATION AND SEA WATER RETURN OUTFALL CHAMBER

Most of the concrete parts of the Sea Water Intake Station and Sea Water Return Outfall Chamber lie in the "Splash Zone" of sea water and are subjected to the salt-laden water, oxygen, and CO_2 of the atmosphere. With alternate wetting and drying severe corrosion of the reinforcement has occurred. The reinforcement expanded owing to the corrosion products, spalled off more concrete and allowed corrosion to proceed further.

A thorough investigation was taken up by the Consulting Engineers [2]. The scope of work included a visual site inspection and sampling of concrete from selected locations for subsequent laboratory analysis to determine strength, composition, porosity, and cement type.

Figures (10) and (11) show the plan, the section and locations of sampling. The results of the chloride test for samples from the pumping station are presented in Tables 1, 2 and 3.

Figure (12) shows the plan, the section and locations of sampling the outfall chamber. The results of the chloride test for samples are presented in Tables 4 and 5.

It can be seen from the results that the level of chloride contamination varied considerably between the structures and was generally higher in the Sea Water Outfall Chamber (1.24% chloride by weight of dried concrete or 6.31% chloride by weight of cement). In several locations the value remained consistently high throughout the full 200 mm depth of concrete tested (from 0.36 to 4.27 % chloride by weight of cement; whereas the maximum permissible % of chloride by weight of cement is 0.3%).

At the Sea Water Pumping Station the level of chloride contamination at the location tested was consistently high at the surface but generally reduced through the initial 120 mm depth of concrete to levels below the limit set by BS 8110, [3].

From the visual site inspection and from the laboratory testing it appears that the generally high level of chloride contamination is the main cause of the deterioration.

Based on the above mentioned results the following material was used in the repair.The material used comprised a proprietary polymer latex modified Portland Cement having the following properties :

1- The flow characteristics of the mixed material is 700 min. No bleed or segregation (Test method: UK-Department of Transport Standard BD27 /86, para.4.6.b).
2- Minimum compressive strength after 3 days 30 N/mm^2 (Test method: BS 1881 ,one day curing in water at 20 °C), [4].
3- Minimum cube compressive strength at 28 days 55 N/mm^2 (Test method: BS 1881).
4- Elastic modulus to satisfy BS 1881 .

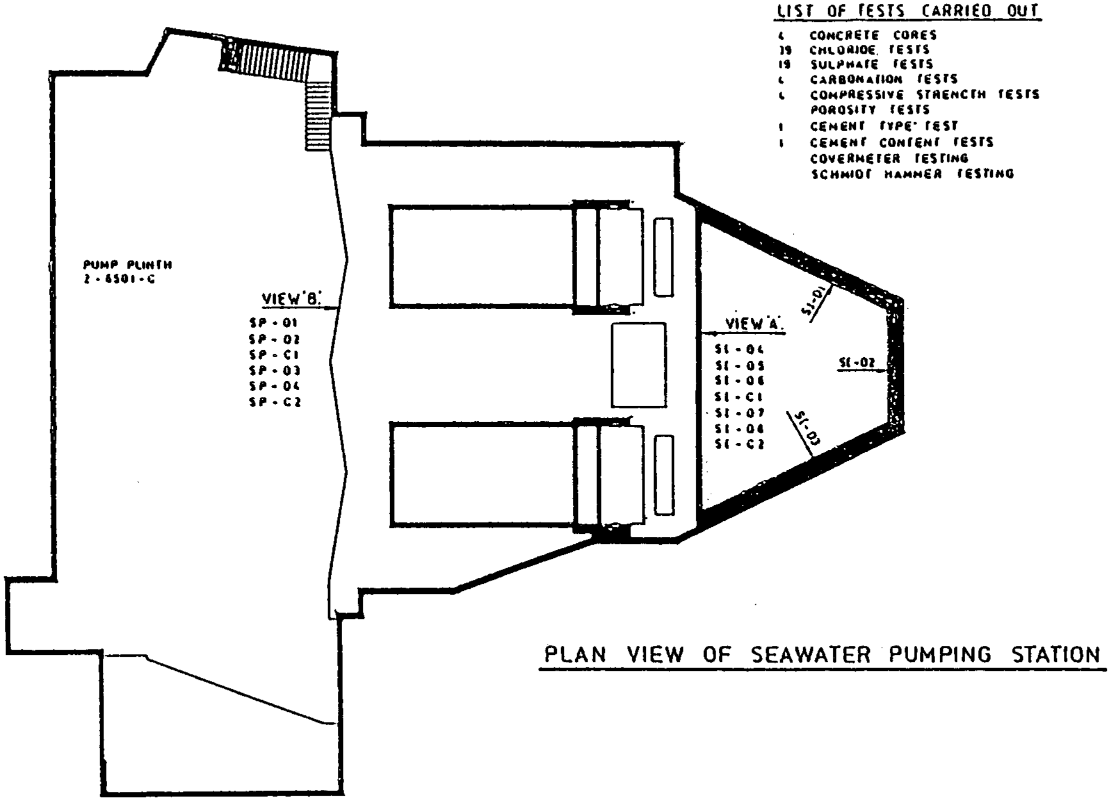


Fig. 10: Concrete investigation test locations

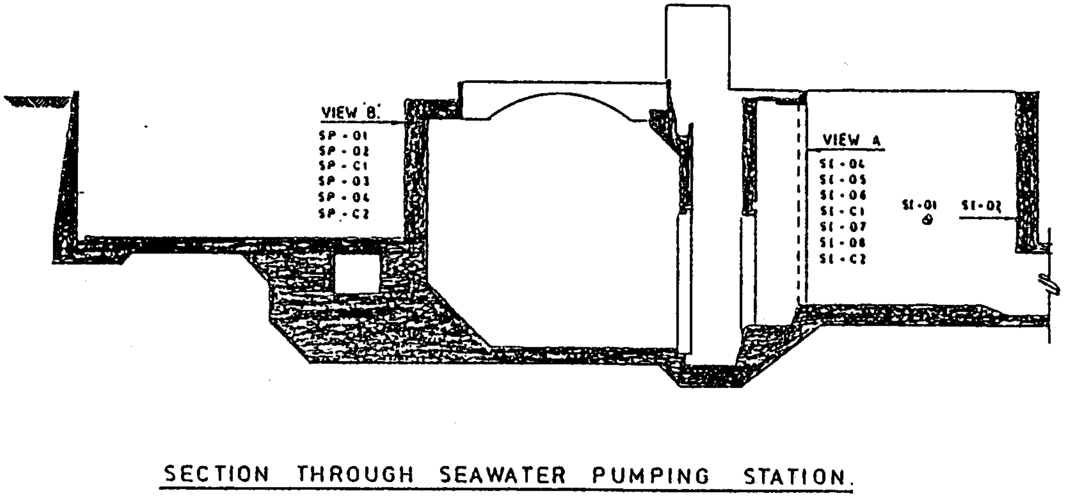


Fig. 11: **Concrete investigation test locations**

Table 1: Results of Chloride Tests on Dust Samples from the Pump Chamber (see Fig. 10)

Location	Depth mm	Chloride % by weight of Dried Concrete.	Chloride % by Weight Of Cement.
SP - D2	0 - 40	0.47	2.39
	40 - 80	0.11	0.56
	80 - 120	0.02	0.10
	120 - 160	0.01	0.05
	160 - 200	0.01	0.05
P-F 2 - 6501 - C	0 - 40	0.43	2.19
	40 - 80	0.07	0.36
	80 - 120	0.01	0.05
	120 - 160	0.01	0.05
	160 - 200	0.01	0.05

Table 2: Results of Chloride Tests on Concrete Cores from the Sea Water Pumping Station (see Figs. 10 & 11)

Location	Position	Chloride % by weight of Dried Concrete.	Chloride % by Weight Of Cement.
SI - C1	TOP	0.57	2.90
	MID	0.03	0.15
	BOT	0.03	0.15
SI - C2	TOP	0.57	2.90
	MID	0.03	0.15
	BOT	0.03	0.15
SP - C1	TOP	0.35	1.78
	MID	0.03	0.15
	BOT	0.03	0.15
SP - C2	TOP	0.43	2.19
	MID	0.03	0.15
	BOT	0.03	0.15

Table 3: Results of Chloride Tests on Dust Samples
from the Intake Chamber (see Figs. 12 & 13)

Location	Depth mm	Chloride % by weight of Dried Concrete.	Chloride % by Weight Of Cement.
S1 - D4	0 - 40	0.25	1.27
	40 - 80	0.07	0.36
	80 - 120	0.04	0.20
	120 - 160	0.03	0.15
	160 - 200	0.03	0.15
S1 - D5	0 - 40	0.44	2.24
	40 - 80	0.04	0.20
	80 - 120	0.04	0.20
	120 - 160	0.02	0.10
	160 - 200	0.02	0.10
S1 - D6	0 - 40	0.58	2.95
	40 - 80	0.09	0.46
	80 - 120	0.01	0.05
	120 - 160	0.01	0.05
	160 - 200	0.01	0.05
S1 -D7	0 - 40	0.81	4.12
	40 - 80	0.07	0.36
	80 - 120	0.01	0.05
	120 - 160	0.01	0.05
	160 - 200	0.01	0.05
S1 - D8	0 - 40	0.21	1.07
	40 - 80	0.03	0.15
	80 - 120	0.01	0.05
	120 - 160	0.01	0.05
	160 - 200	0.01	0.05

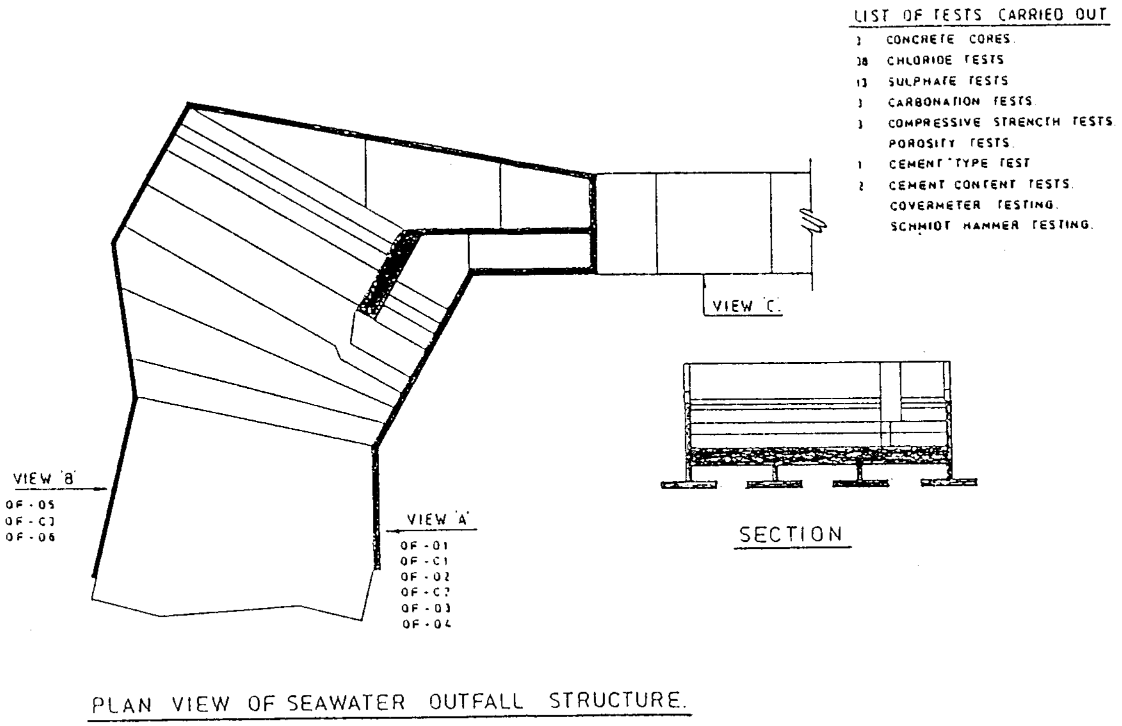


Fig. 12: Concrete investigation test location

Table 4: Results of Chloride Tests on Dust Samples from the Water Outfall Chamber (see Fig. 12)

Location	Depth mm	Chloride % by weight of Dried Concrete.	Chloride % by Weight Of Cement.
OF - D1	0 - 40	1.24	6.31
	40 - 80	084	4.27
	80 - 120	0.64	3.26
	120 - 160	0.57	2.90
	160 - 200	0.55	2.80
OF - D3	0 - 40	0.76	3.87
	40 - 80	0.50	2.54
	80 - 120	0.50	2.54
	120 - 160	0.37	3.56
	160 - 200	0.37	3.56
OF - D5	0 - 40	0.17	0.81
	40 - 80	0.09	0.46
	80 - 120	0.06	0.31
	120 - 160	0.06	0.31
	160 - 200	0.06	0.31
OF - D6	0 - 40	0.21	1.07
	40 - 80	0.10	0.51
	80 - 120	0.07	0.36
	120 - 160	0.07	0.36
	160 - 200	0.06	0.31
OF - D7	0 - 40	0.29	1.48
	40 - 80	0.09	0.46
	80 - 120	0.07	0.36
	120 - 160	0.04	0.20
	160 - 200	0.04	0.26
OF - D8	0 - 40	0.50	2.54
	40 - 80	0.30	1.53
	80 - 120	0.11	1.27
	120 - 160	0.07	0.56
	160 - 200	0.01	0.36

Table 5: Results of Chloride Tests on Concrete Cores for Outfall Chamber (see Fig. 12)

Locatio	Chloride % by Weight Of Dried Concrete	Chloride % by Weight of Cement
OF - C1	0.82	4.17
OF - C2	0.50	2.54
OF -C3	0.51	2.59

5- Maximum chloride ions diffusion coefficient 0.02 cm^2/sec (Test method: cell with disc separating lime water and sodium chloride saturated lime water) [2].

The repair procedure was the same as previously mentioned. Figures (13) and (14) show some parts of the sea water units after two years of repair.

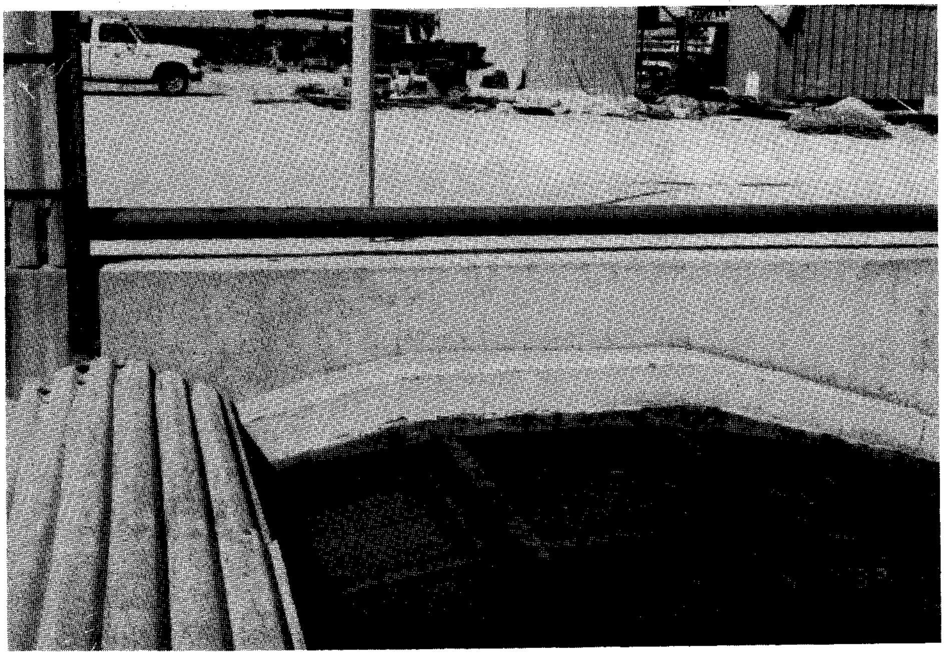


Fig. 13: Water intake wall

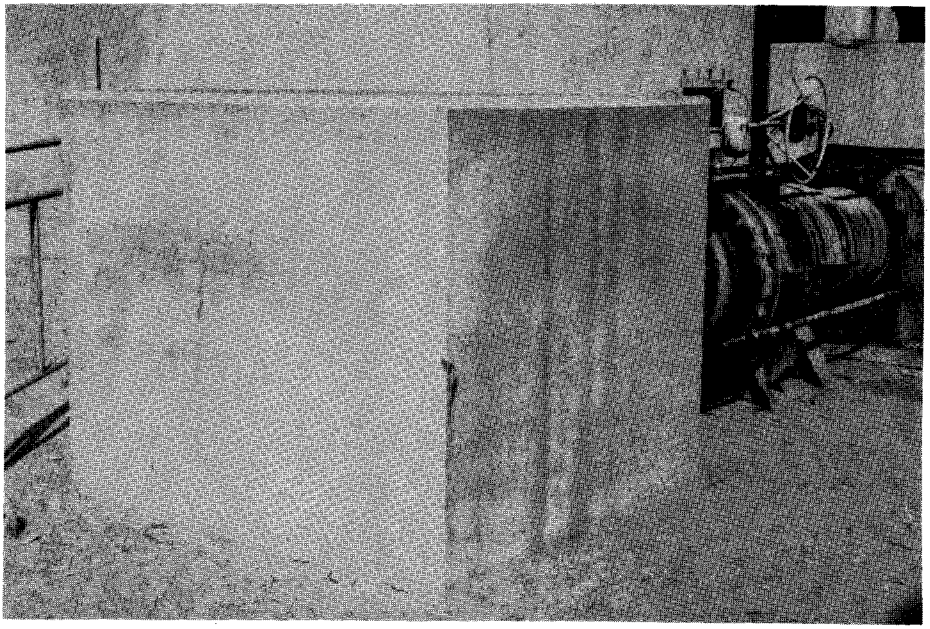


Fig. 14: Sea water unit

CASE 3: DETERIORATION AND REPAIR OF THE CEILING AND THE UPPER PORTION OF THE SIDE WALLS OF UNDERGROUND CONCRETE SULFUR PIT

Sulfur pit is a special reinforced concrete chamber constructed under the ground. It is a part of sulfur producing unit which extracts the sulfur from the feed stock gas (petroleum associated gases or natural gas produced from Qatar North Gas Field) in order to convert these gases to sweet ones and formulate it to "Ethylene Gas" .

The extracted sulfur is accumulated in the liquid state inside the concrete sulfur pit at 150^{O}C. This high temperature is required to keep the sulfur always in the liquid state ready to pump to the periling unit, Figs. (15) and (16).

Two sulfur pits were constructed in the year 1979 with special cement (CLK 325 Cement according to French standard Norm Francis"), [5]. After

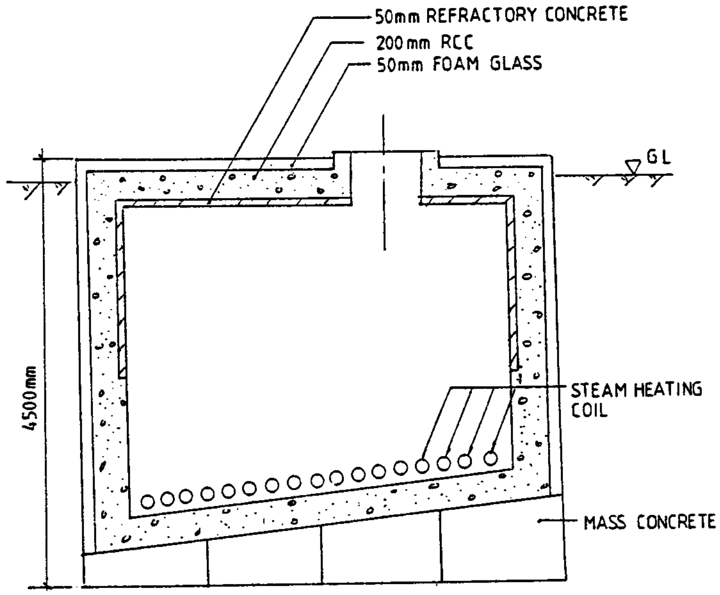


Fig. 15: Details of sulphur pit T-2101

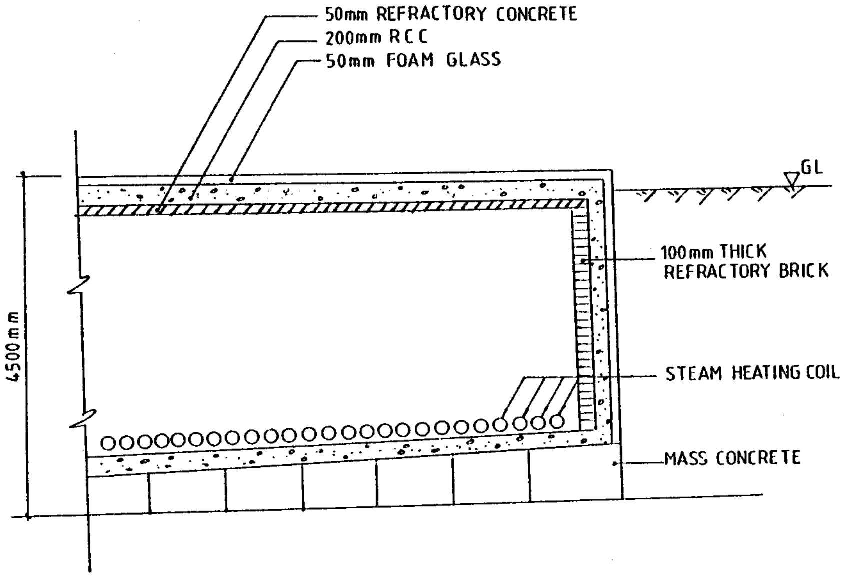


Fig. 16: Details of sulphur pit T-1701

three to four years of construction the ceiling and the internal upper portion of the side walks were delaminated and the reinforcing steel bars became exposed in some parts .

By studying the causes of this delamination it was found that the ceiling and the upper portion of the side walls were exposed to ;

a- Severe corrosive internal environment due to continuous presence of "sulfur vapor" and the occasional presence of mixtures of "sulfuric acids" which form as a result of corrosion of the steam heating coils and consequently admitting the steam to go through the sulfur liquid up to the upper portion of the pit .

b- Internal high temperature which accelerates all the chemical reactions between the concrete and the attacking acids, and causes cracks due to cyclic heating to 150^0 C at starting up and cooling to ambient temperature at shut down periods .

To avoid such delamination a new concrete material had to be used to resist the corrosive / high temperature environment .

By studying the various types of cement it was found that Ordinary Portland Cement, sulfate resistance cement and blast furnace slag cement are not resistant to such corrosive environment existing inside the sulfur pits. However, it was found that "High Alumina Cement" (known as Aluminous or Cement Fondue) could be the suitable type of cement for internal concrete lining . This cement is manufactured from chalk or limestone and bauxite, the latter being an ore of extremely high alumina content. It is resistant to certain forms of chemical attack and in particular, sulfate attack [6].

A ready made "Refractory Concrete" is produced using high alumina cement by international refractors companies under different commercial names (A.P. Green, Plibrico, Kerlane,.etc.) for the purpose of lining the furnaces of petrochemical plants. It resists internal high temperature and the corrosive environment.

In the year 1985 "Plibrico Castable 34 Concrete" which has high alumina cement of 34 % alumina was used in trial repair in one of the sulfur pit by applying 50 mm thick concrete lining. The concrete lining used in the trial should resist the internal high temperature and corrosive environment.

In the year 1987 a new sulfur pit was constructed using "Portland Blast Furnace" cement. The ceiling and the upper 1.5 m of the side walls were lined with 50 mm thick high alumina concrete reinforced by stainless steel wire mesh of 5 mm diameter at 50 mm c/c, Fig. (15). This pit was in service up to the end of 1992 without any deterioration or delamination of the refractory lining or the main construction concrete .

In the year 1991 the ceiling and the upper 1.5 m of the side walls of one of the sulfur pits were completely demolished and reconstructed with Portland Blast Furnace Concrete . The ceiling was lined with the above mentioned high alumina concrete . The side walls were lined for the total height by "High Alumina Bricks" (Fig. 16). The walls were lined with bricks because they are well fabricated and well cured in the manufacturing plant, consequently superior to the concrete which is casted on site. The pit is still in service with very good performance and does not show any sign of deterioration.

NON-DESTRUCTIVE TESTING OF CONCRETE

In 1994, non-destructive testing using the Ultrasonic Pulse Velocity (U.P.V.) tester "PUNDIT" was carried out of the repaired elements. The purpose was to check the condition of concrete and compare the partially repaired with the newly placed concrete .

Six readings were taken on the reconstructed concrete supports for pipe racks at the locations S1 to S6 shown in Figs. (17) and (18). One reading was taken on reconstructed concrete support of high pressure pipe as shown in Fig. (19), location S7.

One reading S8 was taken on the partially repaired Water Intake wall and two readings S11 and S12 on one partially repaired support to Exchanger E-1308-A, Fig. (19).

Readings S9 and S10 are on an old (un-repaired) concrete support to Furnace F-1303 and reading S13 on an old support to Exchanger E-1403, (Fig. 19).

Table 6 summarizes the results of the thirteen U.P.V. readings, the values of concrete compressive strength are taken from the UPV/Strength correlation [7], the given strength is the equivalent of standard cylinder strength. The strength at points S9, S10 and S11 is very high.

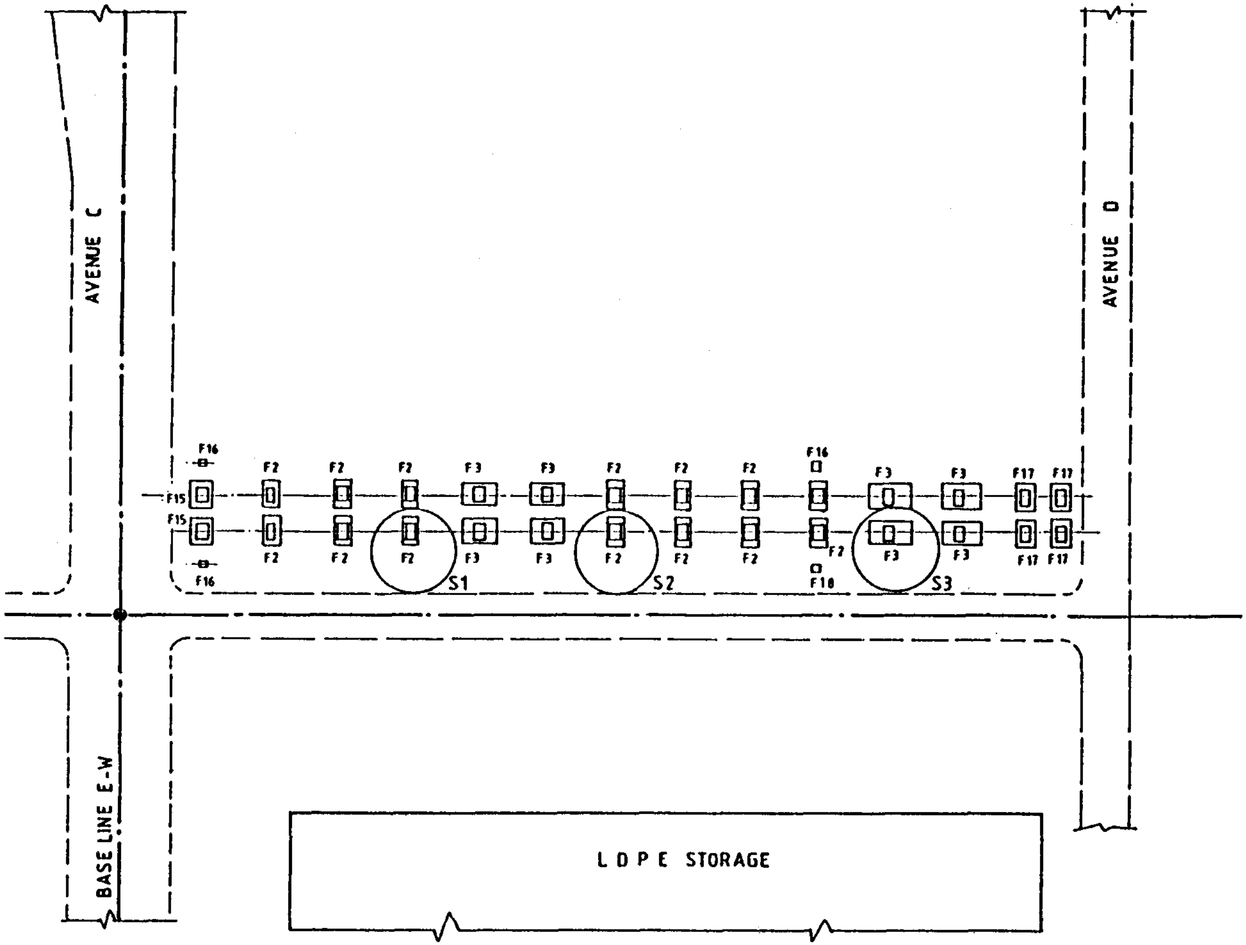


Fig. 17: Location of tested concrete support in pipe rack for U.P.V. test

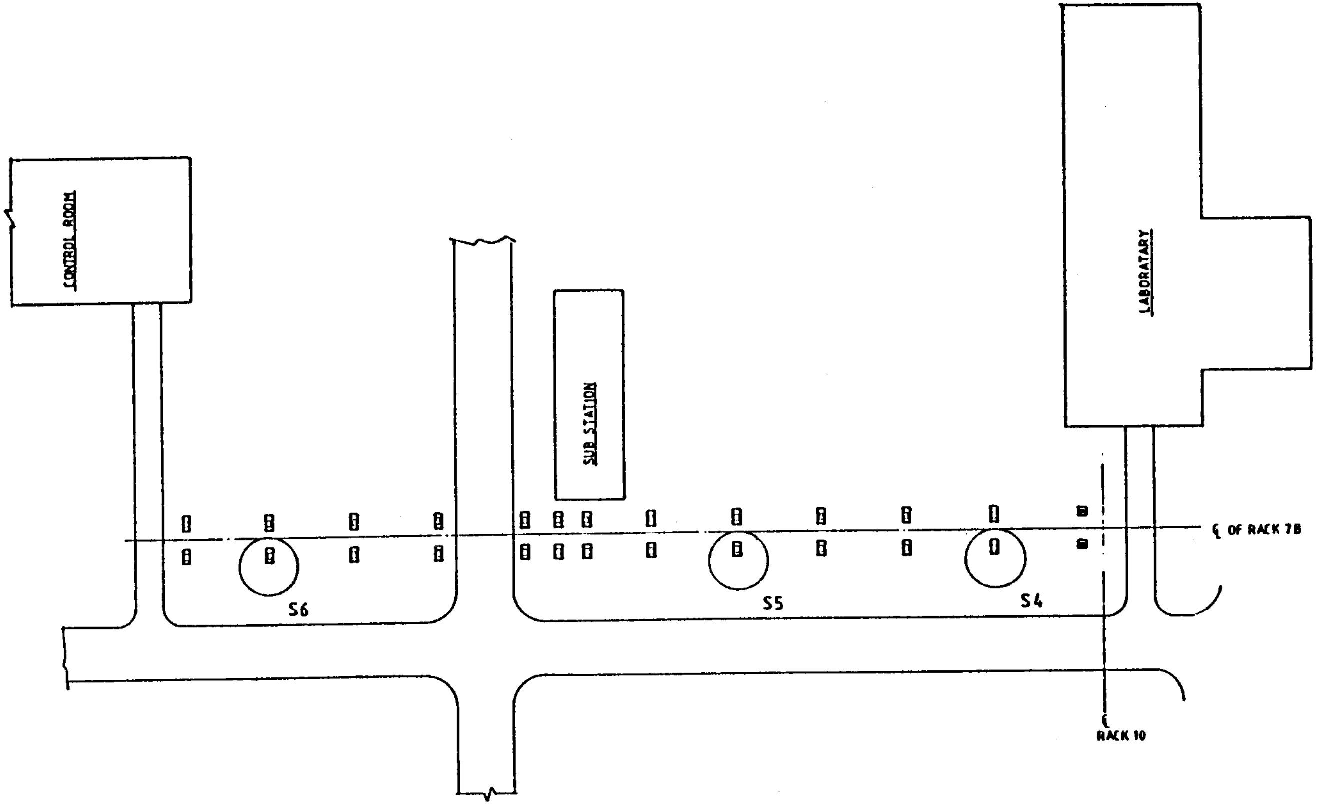


Fig. 18: Location of tested concrete support in LDPE pipe rack No. 7B for U.P.V. test

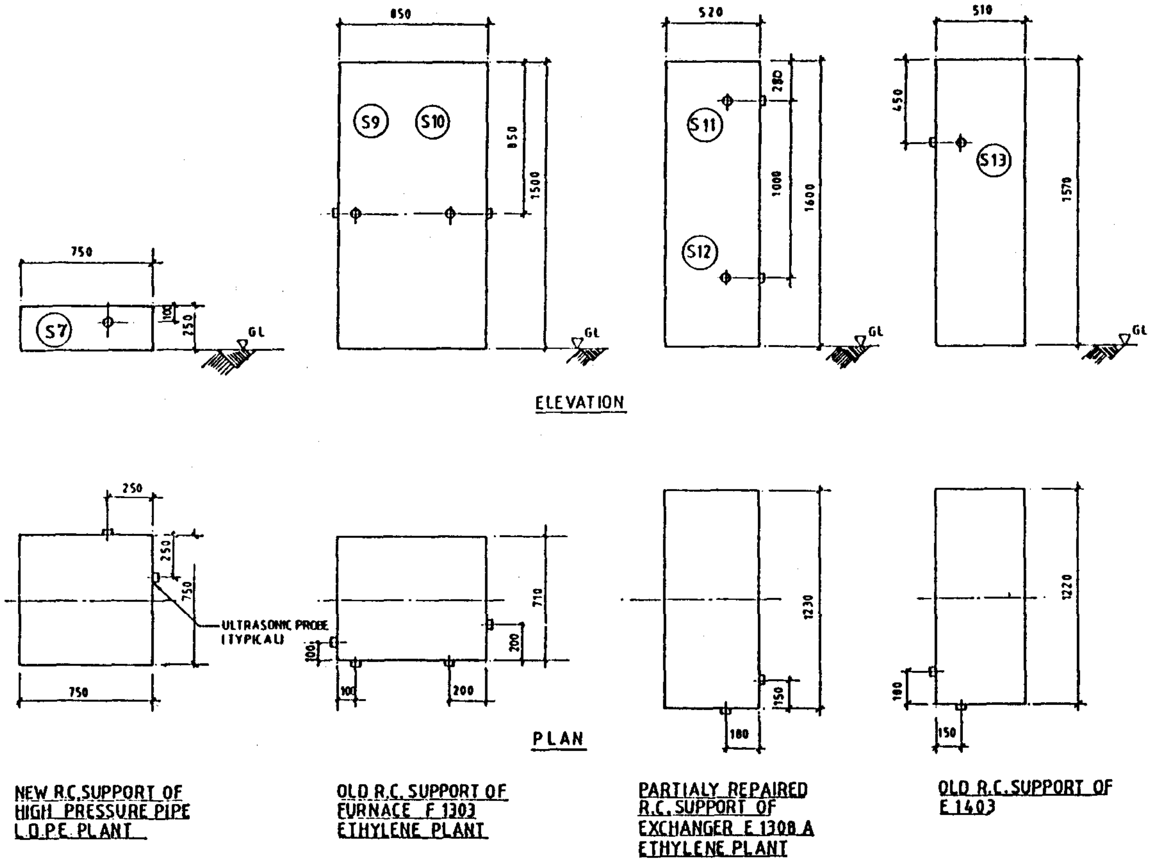
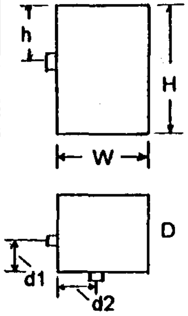


Fig. 19: Location of test point for different R.C. support for U.P.V. test

Table 6: Ultrasonic Tests for QAPCO Concrete Supports

Sr. No.	Sample No.	Sample Location in QAPCO Plants	Drawing No.	Dimensions of the R.C. Support W	D	H	Location Of probe on the R.C.support in mm h	d1	d2	Width Of Measurments in mm	Results of U.P.V. Tests in μ sec.	V in km/sec	av. concrete strength M.Pa	Remarks
1	S1	GOF. Pipe Rack	MGS-356-94	395	600	400	170			370	91.3	4.05	20	** Reading Of These samples were taken diagonally This table to be read with dr. No. MGS-356/7/8-94
2	S2			395	600	400	165			395	97.6	4.05	20	
3	S3			395	600	400	160			395	95.6	4.13	22	
4	S4	Poly -Ethy. Plant Pipe Rack No 7	MGS-357-94	445	445	510	445			445	107	4.16	23	
5	S5			445	455	760	456			445	110.3	4.03	19	
6	S6			437	440	740	440			437	130	3.36	13	
7	S7**	High Prssure Pipe Sup.	MGS-358-94	750	750	250	100	250	250	353.5	79.7	4.44	35	
8	S8	Water Intake Wall		270	7000	500	250			270	71.5	3.78	16	
9	S9**	Concrete Supports Of Furnace F1303	MGS-358-94	850	710	1500	850	100	100	141.4	21	--	--	
10	S10**							200	200	282.8	23	--	--	
11	S11**	Exchanger E1308A Supports	MGS-358-94	520	1230	1600	280	180	150	234.3	48.3	--	--	
12	S12**			150	180		1280	180	150	234.3	52.3	4.48	39	
13	S13**	Exchanger E 1403	MGS-358-94	510	1220	1570	450	150	180	234.3	62.4	3.75	16	

It can be seen from table 6 that the partial repair seems to be more successful at the support of Exchanger E-1308A than at the Water Intake wall . Old concrete strength varies considerably as seen by comparing readings S9, S10 and S13. The reconstructed supports concrete is uniform with medium strength, reading S6 seems to be odd and might be disregarded. It must be noticed, however, that strength is not the only needed property of concrete.

All ultrasonic readings show continuity of the material which indicate that the concrete body is still sound .

CONCLUSION

The above mentioned investigations, analyses and methods of repair of deteriorated concrete structures in an industrial plant in the Arabian Gulf area have been successful. The condition of all repaired concrete after few years of repair is good indicating that the repair procedures are suitable and could be used in similar cases .

There was minimum disruption to production due to the careful investigation done at the planning stage of the repair. The service life of the repaired structure could be extended by employing correct specification of the concrete.

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