RESEARCH AND DEVELOPMENT

Pier in Progreso, Mexico.
Inspection Report
Evaluation of the Stainless Steel Reinforcement
March 1999

ARMINOX Stainless

Pier in Progreso, Mexico

Inspection Report

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RAMBØLL

Job no.: 990022

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Appendices

1. Introduction

This report presents the results of an inspection of the concrete pier in the Port of Progreso, Yucatan, Mexico. RAMBØLL Consulting Engineers and Planners carried out the inspection in December 1998 on the initiative of ARMINOX. The inspection was carried out with the permission and assistance of the Progreso Port Authorities and the assistance of ARMINOX.

The purpose of the inspection was to investigate the general condition of the pier and the condition of the stainless steel reinforcement in selected areas of the pier.

We wish to thank Port Director Agustin J. Arroyo and Sub-manager Miguel Ganzo from the Progreso Port Authorities for their kind help and professional assistance with the inspection.

Figure 1 Location of Pier in Progreso

2. History of the Progreso Pier

2.1 Design and Construction

The 2100 m long concrete pier in Progreso was constructed from 1937 to 1941. It replaced a wooden pier constructed in the beginning of the century. The concrete pier has 175 spans of length 12 m. The concrete pier consists of massive columns and arches.

Due to the harsh environmental exposure of the pier (hot and humid marine environment) in relation to reinforcement corrosion and use of concrete with a relatively high porosity (use of local limestone aggregate), it was decided to use stainless steel reinforcement in selected areas of the pier /1/. Further, the design of the pier allowed for minimum use of reinforcement due to the compressive stresses in the arches.

The pier was cast in 12 m segments and one casting was carried out every three days /1/.

The material consumption was /2/:

Concrete:	Piers/Columns (under water)	32.000 m^3
	Beams, etc.	30.000 m^3
	Pavements, etc.	10.500 m^3
	In total	72.500 m^3
Aggregate:	Fill	57.000 m^3
	Crushed (road pavements, concrete etc.)	113.000 m^3
	In total	170.000 m^3
Cement:	In total	23.000 ton
Steel:	Stainless steel	220 ton
	Other reinforcement	Not stated

2.2 Repairs and Changes

According to the Progreso Port Authorities /3/, the pier has not undergone any major repair work during its lifetime and there has been a complete lack of routine maintenance activities.

In 1988, a 4000 m extension of the pier was completed including container-handling facilities and a RoRo (Roll-on/Roll-off) ramp.

2.3 Neighbour Pier

The remaining parts of a parallel neighbour pier are located approximately 200 m to the west of the investigated pier. The neighbour pier is heavily deteriorated and both columns and superstructure are almost completely gone, see figures 2.1 and 2.2 in Appendix 2.

According to the Progreso Port Authorities /3/, this neighbour pier was built with carbon steel reinforcement approximately 30 years ago. There is severe corrosion damage on exposed reinforcement bars in the columns and deck of the neighbour pier, see figures 2.3 and 2.4 in Appendix 2, and in some cases pitting corrosion occur.

3. Inspection of the Progreso Pier

3.1 Purpose and Extent of Inspection

RAMBØLL carried out the inspection on the 12th and 14th of December 1998. The air temperature was approximately 25^{o}C and the weather was dry with strong on-shore wind.

The purpose and extent of the inspection is described in Table 1.

Due to strong on-shore wind and high waves, it was not possible to inspect the pier from boat. Detailed visual inspection was limited to the arches in span nos. 8 and 9 and column no. 9 between span nos. 9 and 10, see Figure 1.1 in Appendix 1, as these structural parts could be inspected from the beach without a boat. In addition, a superficial visual inspection of span nos. 1 to 7 was carried out from the beach and the remaining spans were inspected very superficially from the superstructure of the pier and the pier head.

Inspection method	Purpose	Extent
Visual inspection	General evaluation of the condition of the pier	Detailed visual inspection of the arches in span nos. 8 and 9 and column no. 9, superficial visual inspection of span nos. 1 to 7 and very superficial inspection of the remaining part of the pier
Covermeter measurements	Location of reinforcement and determination of concrete cover	Superficial inspection of the arches in span nos. 8 and 9 and column no. 9
Break-ups to reinforcement	Evaluation of the extent of corrosion on the reinforcement	Four break-ups in column no. 9
Chloride measurements	Evaluation of the chloride content of the concrete	Three chloride measurements in column no. 9
Petrographic analysis of the concrete	Evaluation of the condition of the concrete	One petrographic analysis of the concrete in column no. 9
Optical emission spectroscopy analysis of the stainless steel reinforcement	Determination of the composition of the reinforcement	One optical emission spectroscopy analysis of the stainless steel reinforcement in column no. 9

Table 1 Purpose and extent of inspection

Column no. 9 is located exactly along the coastline which means that it is heavily exposed to seawater, see figure 1.2 in Appendix 1.

Due to the limited extent of the detailed visual inspection, the inspection cannot form the basis of a general evaluation of the entire pier. However, the condition of the concrete and reinforcement in local areas can be evaluated based on the inspection.

Electro-Chemical Potential (ECP) measurements for identification of areas with high risk of corrosion were not carried out as covermeter measurements of column no. 9 only indicated reinforcement in four spot locations. All these four locations were chosen for break-ups. In addition, the covermeter measurements indicated that the arches were without reinforcement.

3.2 Registrations and Measurements

3.2.1 Visual Registrations

The results of the visual registrations are as follows:

- The pier is generally in a good condition without any significant visible signs of deterioration or corrosion problems, see figures 1.3 to 1.6 in Appendix 1. However, in two specific locations on the west side of column no. 9 corroded reinforcement with no cover was visible (see the last bullet in this list). In general, no significant damage was observed except for casting defects such as honeycombing.

- There are joints between the columns and arches and in the middle of the spans, see figures 1.7 and 1.8 in Appendix 1. No reinforcement is visible in the joints, but a bearing plate is located in the joint between the arches and columns, see figure 1.7 in Appendix 1.

- The arches in span nos. 8 and 9 are generally in a good condition without any visible signs of corrosion problems, see figures 1.9 and 1.10 in Appendix 1.

- There are a few fine longitudinal cracks (crack width less than 1 mm) in the soffit of the arches, see figures 1.8 and 1.11 in Appendix 1. No visible signs of corrosion were observed at the cracks.

- Several honeycombs and other casting defects were located in the soffit and in the outer part of the arches as well as the visible part of the column, see figures 1.12 and 1.13 in Appendix 1. However, no visible signs of corrosion were observed at honeycombing and other casting defects.

- On the west side of column no. 9, reinforcement was visible in two locations. In both locations, the end of a hairpin stirrup was visible (no cover), see figures 1.14 to 1.16 in Appendix 1. In both locations, there was serious laminated corrosion on the visible reinforcement and the reinforcement area was reduced to approximately 60-70%.

3.2.2 Covermeter Measurements

Column no. 9 and the arches in span nos. 8 and 9 were investigated superficially with a covermeter to locate the reinforcement. The covermeter measurements were carried out with the CM9 covermeter from the Protovale Equipment Supplier capable of locating ordinary carbon steel reinforcement up to 20 cm inside the concrete. According to Protovale /4/, the covermeter responds to the electrical conductivity of the metal it locates which means that it is not necessary for the metal to be magnetic to be located by the covermeter. However, if the metal is magnetic, it increases the strength of the signal.

Austenitic stainless steel (e.g. AISI 304 grade) has a very low electrical conductivity, which means that the signals from it are relatively weak. However, the signal strength also depends of the size of the rebar (diameter) and the cover.

The following registrations were made with the covermeter:

- The stainless steel reinforcement (Ø30 mm) with a cover of up to 105 mm could easily be located with the covermeter

- No reinforcement was located in the soffit or in the outer part of the arches in span nos. 8 and 9

- Reinforcement was only located in four positions on column no. 9 (two on the west and two on the east side)

3.2.3 Break-ups to Reinforcement

A total of four break-ups were made to the stainless steel reinforcement in column no. 9. Two break-ups were made on the east side of the column and two on the west side. The location of the break-ups is shown in figure 2 and figures 3.1 and 3.2 in Appendix 3. The visual observations made at the break-ups are reported in Appendix 3.

The concrete was hard and sounding at break-up nos. 1 and 2, and hard, but not sounding at break-up nos. 3 and 4.

There was no corrosion on the reinforcement in break-up nos. 1 and 2 except for light surface corrosion on an area less than 5% in break-up no. 2. The cover was 105 mm in break-up no. 1 and 32 mm in break-up no. 2.

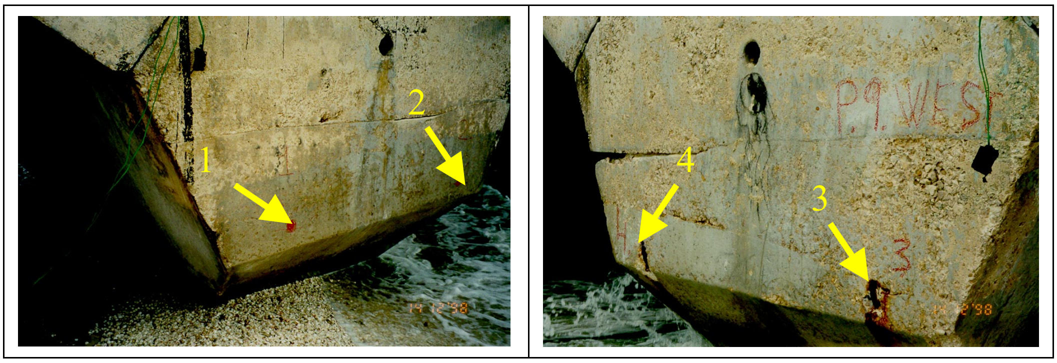

Figure 2 Location of break-ups nos. 1 and 2 (to the left) and 3 and 4 (to the right) on column no. 9

There was serious laminated corrosion on the exposed reinforcement having no cover in break-up nos. 3 and 4. At a depth of 18 mm in break-up no. 3 and 28 mm in break-up no. 4, there was no corrosion on the reinforcement except for light surface corrosion on an area less than 5% of the exposed reinforcement in break-up no. 3 and less than 20% of the exposed reinforcement in break-up no. 4.

3.2.4 Chloride Measurements

All chloride measurements were made by RCT-analysis of dust obtained by hammer drilling for determination of the total acid soluble chloride content of the concrete.

Chloride measurements were carried out at break-up nos. 1, 2 and 3. For each break-up, three holes (Ø16 mm) were drilled and the dust was collected in depths 0-10, 10-20, 20-30, 30-40, 40-60, 60-80 and 80-100 mm from the concrete surface. However, in break-up no. 3 measurements were only carried out to a depth of 60 mm.

The measured chloride contents are shown in graphs in Appendix 4 and in Table 2. Please note that when the samples were collected, the following samples became wet due to high waves:

- Break-up no. 1: 10-20 mm
- Break-up no. 2: 30-40 mm

The chloride content of the seawater in the Atlantic Ocean is approximately 20.000 mg/l and is expected to be higher in the Mexican Gulf. The fact that two samples became wet has probably increased the measured chloride content of the two samples. The chloride profiles in Appendix 4 seems to confirm this, but the effect of the wetting does not seem to be very significant.

The chloride analyses show very high chloride contents in all depths. The chloride content is mostly within the range of 0.6 to 1.0% Cl^- of dry concrete weight. To verify the very high chloride contents determined by RCT-analysis, the following three samples were selected to be analysed by potentiometric titration also:

- Break-up no. 2: 0-10 mm and 20-30 mm
- Break-up no. 3: 10-20 mm

The results of the potentiometric titration are shown in brackets in Table 2 and the results from the two different chloride analyses show relatively good conformity. Based on this, the high chloride results from the RCT-analyses are considered verified.

Location	Chloride content [% Cl^- of dry concrete weight]						
Depth, mm	0-10	10-20	20-30	30-40	40-60	60-80	80-100
Break-up 1	0.92	1.35[1]	0.92	0.85	0.75	0.64	0.64
Break-up 2	0.82 (0.73)	0.89	1.18 (1.05)	1.18[1]	0.89	0.82	0.72
Break-up 3	0.96	1.24	1.92 (1.81)	1.54	1.04	[2]	[2]

Note 1: The sample became wet (seawater)

Note 2: No chloride measurement

Table 2 Chloride content at break-ups determined by RCT-analysis. Values determined by potentiometric titration are shown in brackets.

3.2.5 Petrographic Analysis of Concrete

A relatively small concrete sample was taken from column no. 9 at break-up no. 3 for petrographic analysis. The result of the petrographic analysis carried out by the G.M. Idorn Consult concrete laboratory is shown in Appendix 5.

The fine and coarse aggregate consists of angular to rounded grains of limestone with a nominal maximum size of the coarse aggregate of approximately 25 mm. The distribution in the concrete is uniform and the content of coarse aggregate is approximately 35 %.

The cement used in the concrete is a relatively medium to coarse grained Portland cement. Fly ash or micro silica is not observed in the sample. The cement paste shows some variations in capillary porosity ranging from a w/c ratio of 0.50 to approximately 0.70, with a mean w/c ratio of approximately 0.55-0.60. The paste content is relatively high.

The concrete appears to be non air-entrained. Some irregular to circular air voids are observed in the concrete.

The concrete contains a relatively high amount of fine plastic paste and adhesion cracks. These cracks are partly filled with portlandite ($Ca(OH)_2$), indicating internal bleeding of the concrete. The mean carbonation depth is low and varies from approximately 0 to 0.5 mm. The paste is, however, partly carbonated around air voids and porosities throughout the sample.

There are no signs of alkali-silica reactions or sulphate attack in the concrete.

3.2.6 Optical Emission Spectroscopy Analysis of Stainless Steel Reinforcement

A reinforcement sample was taken from column no. 9 at break-up no. 3 (exposed reinforcement) for optical emission spectroscopy analysis. The result of the analysis carried out by the FORCE Institute is shown in Appendix 6.

The chemical analysis and metallographic examination of the stainless steel sample carried out at the FORCE Institute show that the steel quality is comparable to the common AISI 304-grade (also known as the 18-8-grade).

The steel sample is heavily attacked by stress corrosion cracking. Stress corrosion cracking is caused by tensile stresses in the reinforcement probably due to mechanical impact during production of the reinforcement or handling on the construction site, e.g. bending. The severe laminated corrosion on the freely exposed reinforcement suggests stress corrosion. However, even without the presence of stress corrosion cracking, serious corrosion attack of freely exposed reinforcement can be expected due to the aggressive conditions on freely exposed reinforcement surfaces such as high temperatures due to sunlight, free access of oxygen and severe chloride exposure. These conditions may result in pitting corrosion.

For reinforcement totally embedded in the concrete, the same critical conditions can not be expected as the temperature and chloride content will be lower. In addition, the reduced access of air and the alkalinity of the concrete will reduce the risk of corrosion for steel embedded in concrete.

3.3 Evaluation of Registrations and Measurements

The purpose of the present investigation of the reinforcement in the concrete pier in Progreso is to evaluate the performance of embedded stainless steel in a harsh saline and subtropical environment.

The design of the pier has resulted in minimum use of reinforcement, which has been confirmed by covermeter measurements.

Based on a superficial visual inspection, the general condition of the pier is good, especially considering the harsh environment in relation to corrosion and the relatively high porosity of the concrete. No signs of alkali-silica reactions or sulphate attack were found in the small concrete sample. Mean carbonation depths of 0 to 0.5 mm were measured in the concrete sample, but the sample was sporadically carbonated in the outer 0-35 mm.

No serious signs of corrosion of the stainless steel reinforcement embedded in the concrete were found. However, corrosion was detected on the freely exposed reinforcement (no cover) as could be expected, refer to Appendix 6. For reinforcement with a cover larger than approx. 20 mm, there was no significant corrosion on the bars despite the extremely high chloride contents of up to 1.9% Cl^-, which is at least 10 times of what is normally regarded as critical for initiation of corrosion on ordinary carbon steel. This observation confirms the assumption made in Appendix 6 that stainless steel bars embedded in concrete presumably are well protected against corrosion.

Based on the limited number of chloride measurements, it seems that the west side of the pier has higher chloride content than the east side (approx. 35% in average).

The petrografic analysis shows that the concrete sample is sporadically carbonated in the outer 0-35 mm. This may push the chlorides deeper into the concrete because the bounded chloride will be partly released.

Even under very conservative assumptions (use of wet corals as aggregate and sea water as mixing water), the maximum amount of cast-in chloride can be estimated to approximately 0.3% Cl^-. The chloride content measured at depths 80-100 mm (0.6 to 0.7% Cl^-) indicates that much chloride has penetrated to this level which is not surprising considering the age of the pier, the saline environment and the relatively high porosity of the concrete. Based on the limited number of samples taken from the pier, it has not been possible to determine whether the chlorides at present are free and therefore available for initiation of chloride induced corrosion on the reinforcement or whether the chlorides have been bound physically and/or chemically in the concrete during the 60-years lifetime.

An estimate of the maximum initial chloride content is given above. However, all of these chlorides have not been free and available for initiation of corrosion during the entire lifetime of the pier, as a larger and larger part of the cast-in chlorides will be physically and/or chemically bound with age. The use of carbon steel reinforcement embedded in concrete with an initial chloride content of approximately 0.3% Cl^- would most probably have resulted in serious pitting corrosion on the reinforcement after a few years, because the cast-in chlorides would be free in a period after the construction of the pier.

For a reinforced concrete structure in marine environment with ordinary embedded carbon steel, the lack of routine maintenance for a 60-year period would in many cases result in serious chloride or/and carbonation induced corrosion problems as clearly shown by the deterioration of the neighbour pier located to the west of the inspected pier. The use of the AISI 304-grade stainless steel as reinforcement has probably contributed significantly to the good visual appearance of the Progreso pier.

4. Conclusion

Based on the present investigation of the Progreso pier, it must be concluded that the choice of stainless steel as reinforcement has been an intelligent choice of material. Despite the saline and subtropical environment combined with the use of concrete with relatively high porosity and some casting defects, no significant corrosion problems have been observed for the AISI 304-grade stainless steel reinforcement except for areas were the reinforcement has been exposed (no cover) for a 60-year period.

For the Progreso pier, the use of stainless steel reinforcement has reduced the routine maintenance cost to almost nothing and the pier is still performing very well with almost no sign of deterioration.

Based on the condition and age of the pier, and the limited number of investigations carried out in this inspection, we estimate the remaining service lifetime to be at least 20 to 30 years even without any significant routine maintenance activities.

5. References

/1/ Christiani & Nielsen, 40 year jubilee publication, 1904-1944

/2/ Christiani & Nielsen, 50 year jubilee publication, 1904-1954

/3/ Personal communication with the Progreso Port Authorities, December 1998

/4/ Protovale Equipment Supplier, Information on the CM9 covermeter, January 1999

Appendix 1
Visual Inspection of Pier

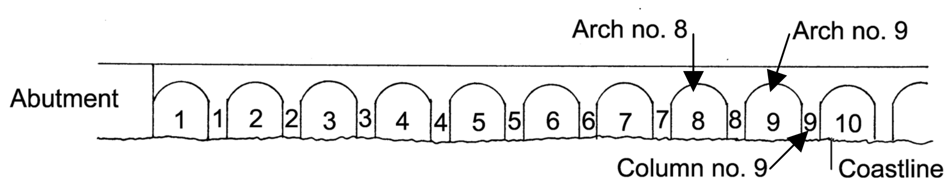

Figure 1.1 Sketch showing the areas selected for detailed visual inspection

Figure 1.2 East side of column no. 9 located along the coastline

Figure 1.3 West side of the pier

Figure 1.4 East side of the pier

Figure 1.5 Pier columns near pier head

Figure 1.6 Pier column near pier head

Figure 1.7 Joint gab and bearing plate between column and arch, column no. 9

Figure 1.8 Joint gab and longitudinal crack in the soffit of the arch at the mid of the span

Figure 1.9 Arch in span no. 9, west side

Figure 1.10 Arch in span no. 8, west side

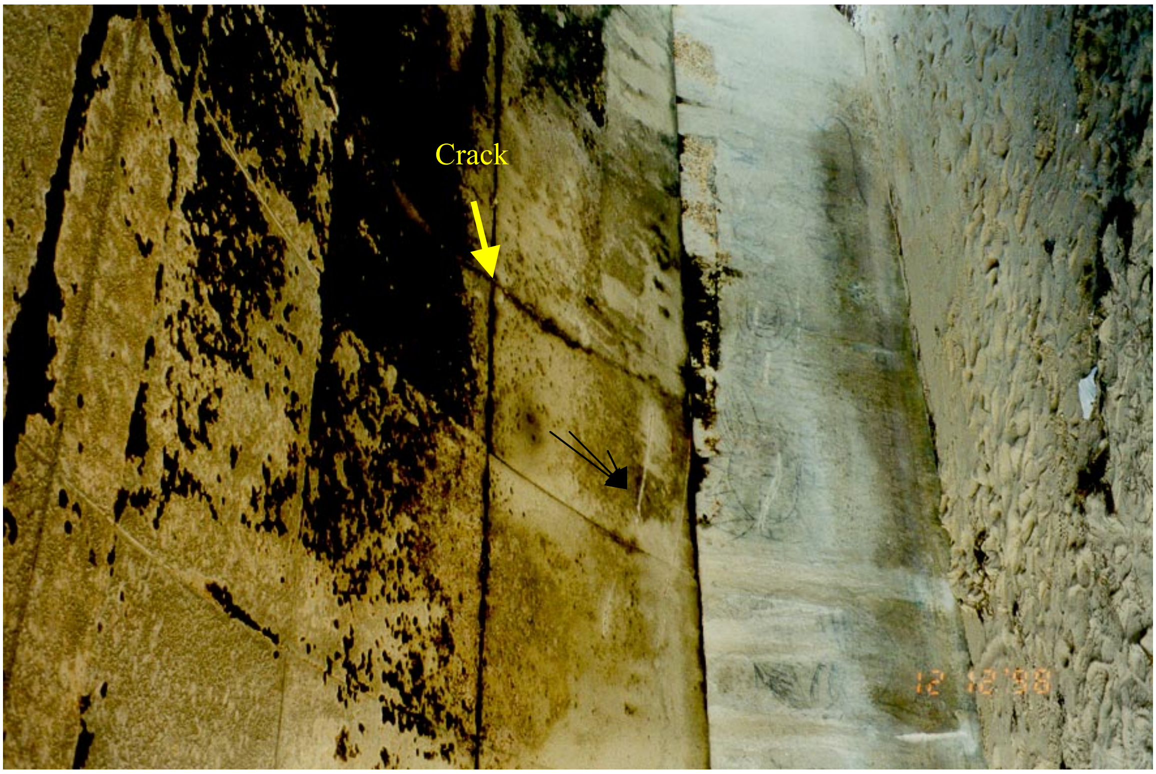

Figure 1.11 Longitudinal crack in the soffit of the arch

Figure 1.12 Honeycomb at the edge of the arch in span no. 9

Figure 1.13 Casting defect in the soffit of the arch

Figure 1.14 Visible reinforcement on west side of column no. 9

Figure 1.15 Visible reinforcement on west side of column no. 9

Figure 1.16 Visible reinforcement on west side of column no. 9

Appendix 2
Visual Inspection of Neighbour Pier

Figure 2.1 Deteriorated concrete columns of neighbour pier located to the west of the inspected concrete pier

Figure 2.2 Deteriorated concrete columns of neighbour pier located to the west of the inspected concrete pier

Figure 2.3 Pier deck of the neighbour pier

Figure 2.4 Pier deck of the neighbour pier

Appendix 3
Break-ups to Reinforcement in Column No. 9

Figure 3.1 Location of break-ups 1 and 2, east side of column no. 9

Figure 3.2 Location of break-ups 3 and 4, west side of column no. 9

Break-up no. 1 Location: Column no. 9, east side, see Figure 3.1		
Structural part	**Description**	**Figure no.**
Concrete	The concrete was hard and sounding. Chloride measurements were carried out.	3.1
Reinforcement	Vertical reinforcement (hairpin stirrup): - Cover 105 mm - Bar Ø30 mm - No corrosion (glossy)	3.3 3.4

Figure 3.3 Concrete and reinforcement at break-up no. 1

Figure 3.4 Reinforcement at break-up no. 1

Break-up no. 2 Location: Column no. 9, east side, see Figure 3.1		
Structural part	**Description**	**Figure no.**
Concrete	The concrete was hard and sounding. Chloride measurements were carried out.	3.1
Reinforcement	Vertical reinforcement (hairpin stirrup): - Cover 32 mm - Bar Ø30 mm - No corrosion (glossy) except for a very small area (< 5%) with light surface corrosion	3.5 3.6

Figure 3.5 Concrete and reinforcement at break-up no. 2

Figure 3.6 Reinforcement at break-up no. 2

Break-up no. 3 Location: Column no. 9, west side, see Figure 3.2		
Structural part	**Description**	**Figure no.**
Concrete	The concrete was hard, but not sounding. Large honeycombs were located just above the break-up. Chloride measurements were carried out. A concrete sample was taken out for petrographic analysis.	3.2 3.7 3.8
Reinforcement	Vertical reinforcement (hairpin stirrup): - Cover 0 mm (visible reinforcement) - Bar Ø30 mm - Serious laminated corrosion on reinforcement part with no cover - 18 mm inside the concrete there was no corrosion except for light surface corrosion on a very small area (< 5%) - A reinforcement sample was taken out for optical emission spectroscopy analysis. After the reinforcement sample was taken out, the reinforcement area was reduced to approximately 20-30%.	3.9 3.10 3.11

Figure 3.7 Concrete at the west side of column no. 9, break-up nos. 3 and 4

Figure 3.8 Concrete and exposed reinforcement at break-up no. 3

Figure 3.9 Reinforcement at break-up no. 3 (after break-up)

Figure 3.10 Reinforcement at break-up no. 3 (after break-up)

Figure 3.11 Reinforcement at break-up no. 3 (after removal of reinforcement sample)

Break-up no. 4 Location: Column no. 9, west side, see Figure 3.2		
Structural part	**Description**	**Figure no.**
Concrete	The concrete was hard, but not sounding. Large honeycombs were located just above the break-up.	3.2 3.7
Reinforcement	Vertical reinforcement (hairpin stirrup): - Cover 0 mm (visible rein-forcment) - Bar Ø30 mm - Serious laminated corrosion on reinforcement part with no cover (reinforcement area is reduced to approx. 40-50%) - 28 mm inside the concrete, there was no corrosion except for light surface corrosion on a limited area (< 20%)	3.12 3.13

Figure 3.12 Reinforcement at break-up no. 4 (after break-up)

Figure 3.13 Reinforcement at break-up no. 4 (after break-up)

Appendix 4
Results of Chloride Measurements

The graphs in this Appendix show the total acid soluble chloride content of the concrete (%Cl^- of dry concrete weight) as a function of the depth behind the surface. In the graphs the values determined by potentiometric titration are shown in brackets. For samples that became wet (seawater), the chloride content is written in *italic*.

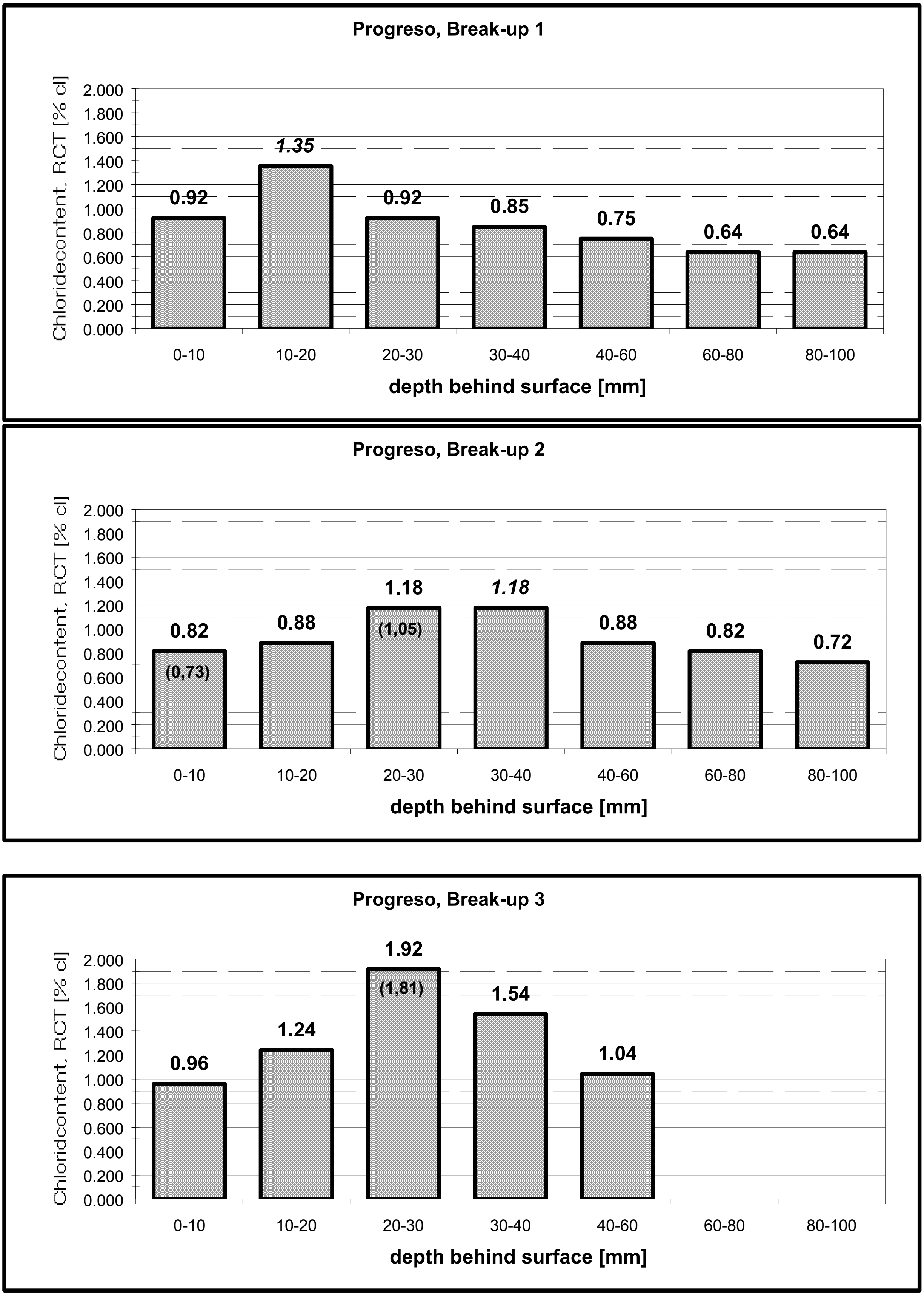

Figure 4.1 Chloride measurements at break-up 1, 2 and 3

Appendix 5
Results of Petrografic Analysis of Concrete

PETROGRAPHIC ANALYSIS OF A CONCRETE SAMPLE FROM PIER IN PROGRESO

G.M.Idorn Consult, Rambøll

February 1999

Job	990022		
Ref.No.	990022r.001	Prepd.	BNG
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1. Introduction

On request of stainless steel producer Arminox, G.M. Idorn Consult, RAMBØLL has performed petrographic analysis of one concrete sample from the concrete pier in the Port of Progreso, Yucatan, Mexico.

The sample was received at G.M. Idorn Consult's concrete laboratory in Virum December 18, 1998

2. Objectives

The aim of this investigation is to obtain an overall view of the quality of the concrete.

3. Test programme

The core was marked:

Sample No.	GMIC Lab.No.	Comments
Column 9	21798	Break-up no. 3

The core is hereafter referred to by the sample No. given above.

Microanalysis has been carried out on one thin section made from the sample. The thin section was placed perpendicular to the exposed surface of the sample.

4. Summary

The results of the petrographic analysis are summarised in the following:

The concrete in the sample has following characteristics:

Aggregate
The fine and coarse aggregate consists of angular to rounded grains of limestone. The nominal max. size of the coarse aggregate is approx. 25 mm. The distribution in the concrete is uniform and the content of coarse aggregate is approx. 35 %.

Cement paste
The cement used in the concrete is a relatively medium to coarse grained Portland cement. Fly ash or micro silica is not observed in the sample. The cement paste shows some variations in capillary porosity throughout section ranging from a w/c ratio of 0.50 to approx. 0.70, with a mean w/c ratio of approx. 0.55-0.60. The paste content is relatively high.

The concrete appears to be non air-entrained. Some irregular to circular air voids are observed in the concrete.

The concrete contains a relatively high amount of fine plastic paste and adhesion cracks. These cracks are partly filled with portlandite ($Ca(OH)_2$), indicating internal bleeding of the concrete. The mean carbonation depth is low and varies from approx. 0 to 0.5 mm. The paste is however partly carbonated around air voids and porosities throughout the sample.

There are no signs of alkali-silica reactions or sulphate attack in the concrete.

Surface
A thin relative dense layer (approx. 0.5 mm) of calcium carbonate is observed on the surface.

5. Analytical Methods and results

Petrography
The petrographic examination consists of a macroscopical and microscopical examination of the concrete samples.

The macroscopical examination is performed by the naked eye and by use of a stereo microscope. The sample is photographed with GMIC sample no. and scale.

The microscopical examination is carried out on one fluorescent impregnated thin section.

The thin section is made by vacuum impregnating a slice from the sample with an epoxy resin containing a fluorescent dye. Subsequently, the impregnated slice is mounted on a glass plate and ground and polished to a thickness of 0.020 mm. The thin section is examined in a polarizing optical microscope using transmitted light, crossed polarizes and blue transmitted light with a yellow blocking filter (fluorescent mode). The vacuum impregnation of the sample with epoxy causes all voids and cavities in the samples to be filled with fluorescent epoxy. By transmitting blue light through the thin section in the microscope, the fluorescent epoxy in the various porosities will emit yellow light that makes voids, cavities and cracks easy to identify. The fluorescent epoxy also impregnates the capillary pores in the hardened cement paste causing a dense cement paste with low water to cement ratio to appear darker green while a more porous cement paste with a high water to cement ratio appears lighter green. By comparing the green colour of the cement paste of the samples with known standards the water to cement ratio (w/c) can be estimated. The accuracy of the estimation is normally ± 0.02.

MACRO-DESCRIPTION

Case Number: 990022 **Date:** 25/1-1999
Sample No.: Column no. 9, Break-up no. 3
Location: Concrete pier in Port of Progreso
GMIC lab. no.: 21798

Sample Dimensions (mm): **Length:** se sketch. **Diameter:** se sketch.

Coarse Aggregate: Angular to rounded limestone, with a nominal max. size of approx. 25 mm.

Cement Paste: Greyish white.

Top Surface: Plane surface with thin greyish layer of ? .

Bottom surface: Broken surface.

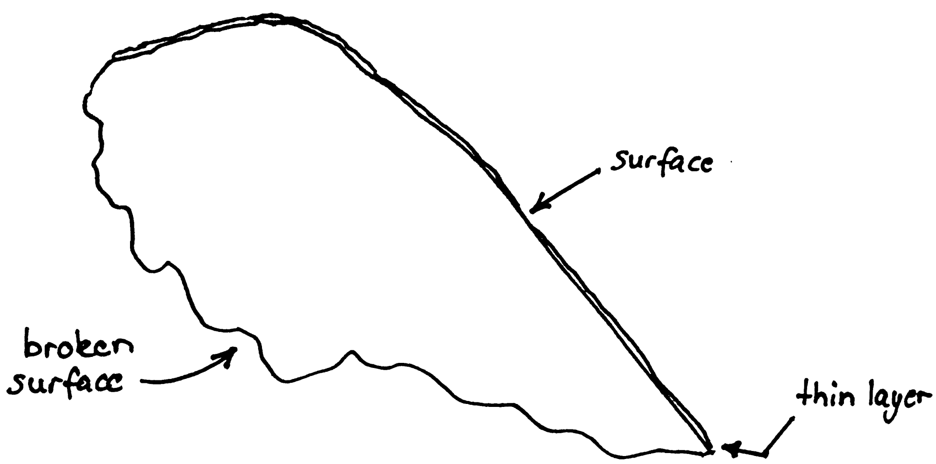
Cracks (visible): No cracks are observed.

Carbonation (mm): ~ 0 , (tested with phenolphthalein).

Reinforcement:
(Nos. sizes and covers) None.

Remarks: Few entrapped air voids are observed.

Sketch of Sample (1 : 1): Surface to the right



MICRO-DESCRIPTION

Case Number: 990022 **Thin Section No.:** 21798 **Date:** 27/1-1999
Sample No.: Column no. 9, break-up no. 3

Aggregates, type, size, and shape
Coarse aggregate (>2 mm): Angular to rounded limestone.
Fine aggregate (< 2 mm): Angular to rounded limestone.

Cement paste
Cement type: Relatively medium to coarse grained Portland cement.
Mean w/c ratio: 0.55-0.60
Variation in w/c ratio : 0.50-0.70

Cracks
Coarse (> 0.1 mm): None.
Fine: Some to many plastic cracks partly filled with $Ca(OH)_2$.
Micro (< 0.01 mm): Few.

Crack and/or pore filling
Ettringite: Little to some.
Portlandite, $Ca(OH)_2$: Some.

Air content (estimated-%): Low, approx. 1-2 %.

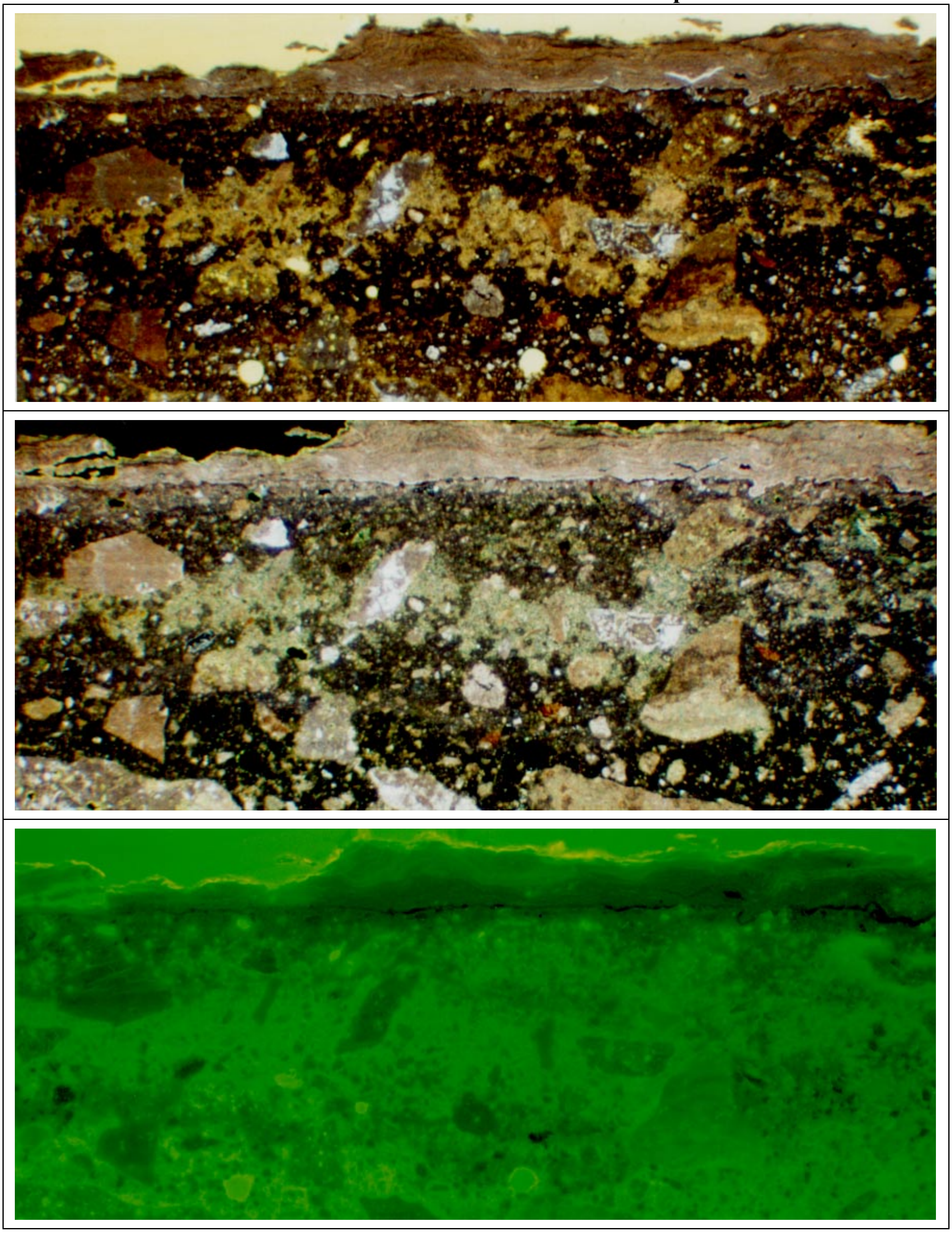
Carbonation depth
Mean surface (mm): 0, partly carbonated throughout section.
Along cracks (mm): -

Remarks:

The concrete appears to be non air-entrained. The presence of paste and adhesion cracks partly filled with $Ca(OH)_2$ indicate internal bleeding of the concrete.

PHOTO DOCUMENTATION

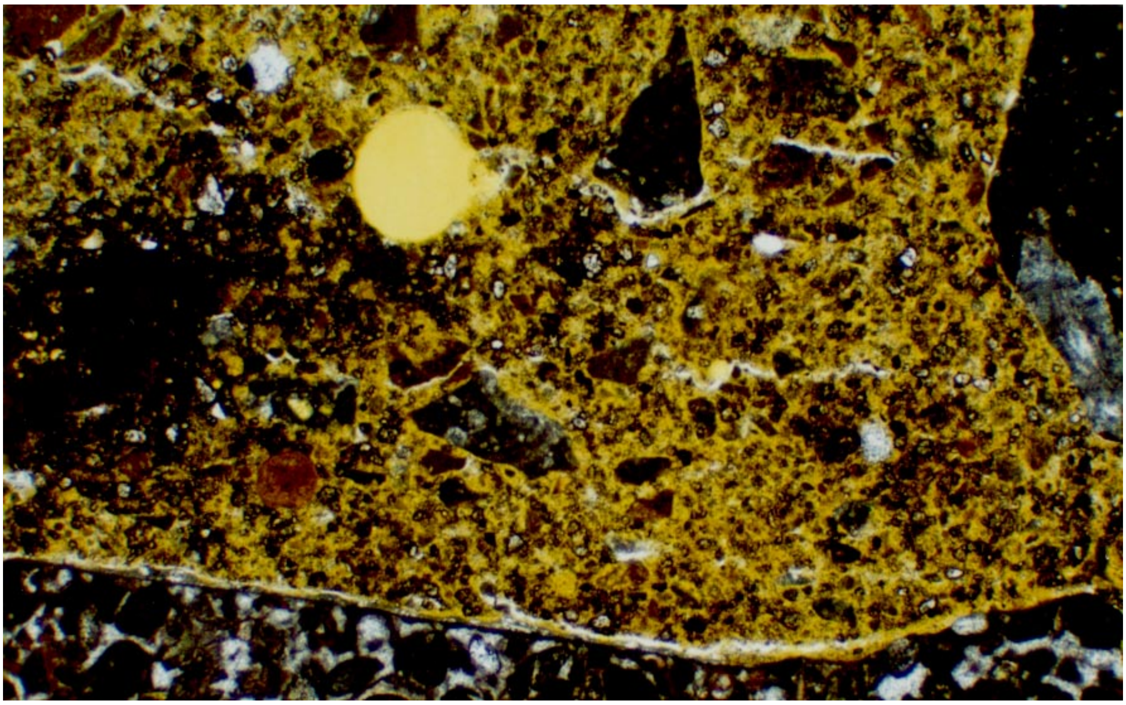
Case No.: 990022 **GMIC. No.:** 21798 **Sample No.:** Column no. 9

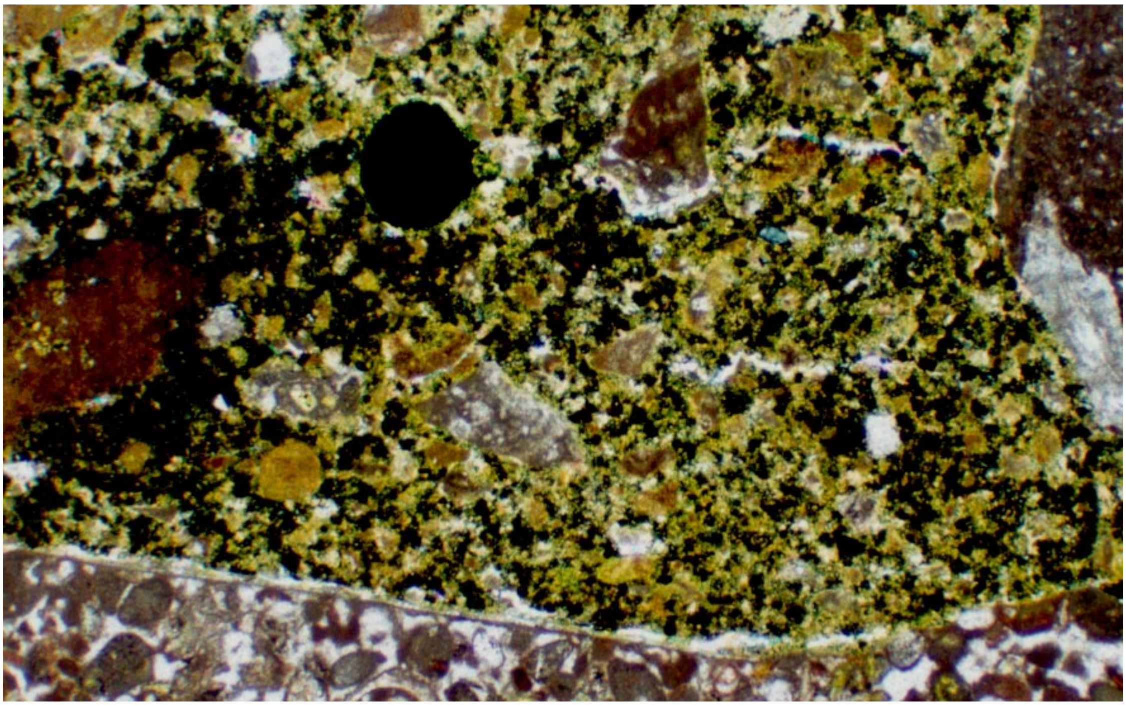


Micrographs showing the surface of the concrete. A thin relative dense layer of carbonate is seen cover the concrete surface. The photos are taken in ordinary, crossed polarized and fluorescent light (same field of view): approx. 6 x 3 mm.

PHOTO DOCUMENTATION

Case No.: 990022 **GMIC. No.:** 21798 **Sample No.:** Column no. 9

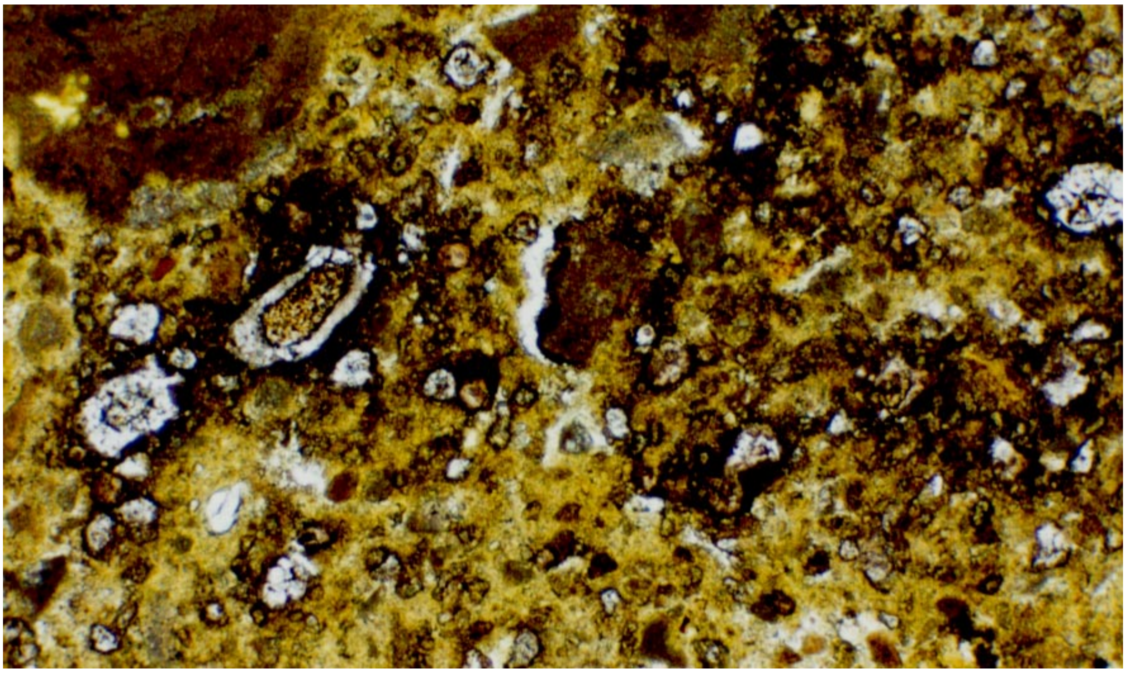


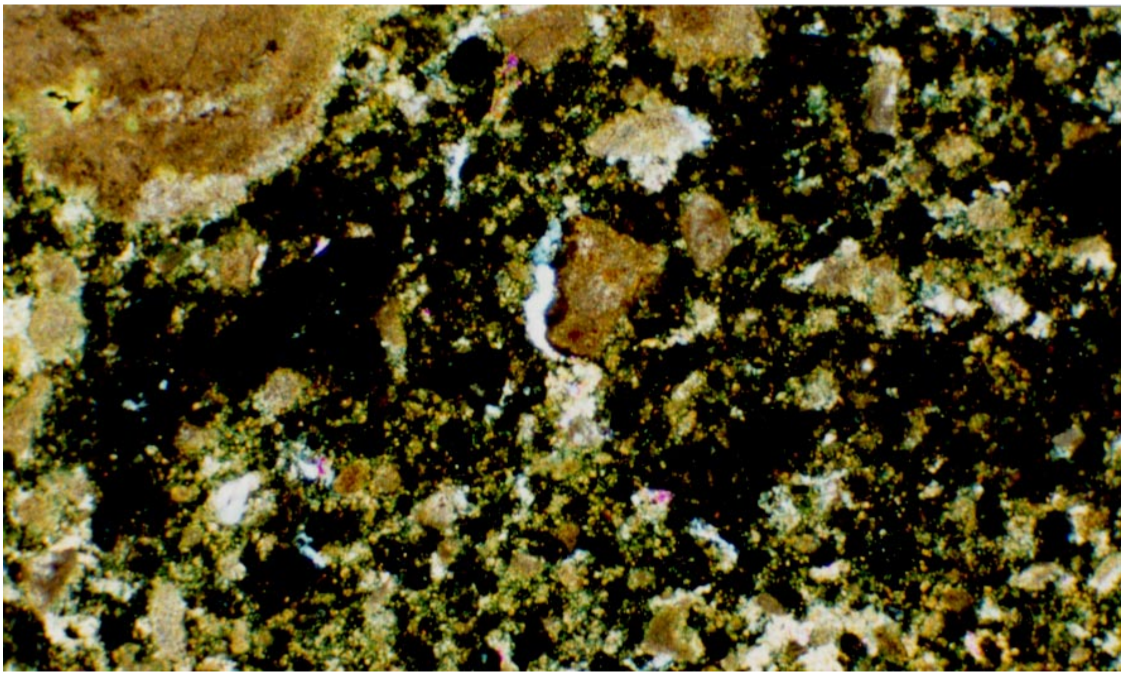


Micrographs showing a relatively high amount of fine plastic paste and adhesion cracks. The cracks are partly filled with Ca $(OH)_2$. The photos are taken in ordinary and crossed polarized light (same field of view) approx. 4.2 x 2.7 mm.

PHOTO DOCUMENTATION

Case No.: 990022 **GMIC. No.:** 21798 **Sample No.:** Column no. 9





Micrographs showing a typical area of paste with some unhydrated cement grains. The paste is partly carbonated (brownish on lower photo). The photos are taken in ordinary and crossed polarized light (same field of view), approx. 1.5 x 1 mm.

Appendix 6
Results of Optical Emission Spectroscopy Analysis of Stainless Steel Reinforcement

FORCE INSTITUTE

ARMINOX ApS.
Att.: Preben Nielsen
Fabriksvej 6, Mønsted
8800 Viborg

Your ref.
Our ref. K9-7326/TRM/sh
Division Materials and Chemical Analysis
Date 11-01-99

Re.: Evaluation of Stainless Steel Sample from a Bridge Pier at Puerto Progreso

On request from ARMINOX ApS, the FORCE Institute's Corrosion Department has investigated a stainless steel sample taken from a pier of the Puerto Progreso Bridge in Mexico. The aim of the investigation was to evaluate the quality of the stainless steel.

Background

The investigated sample (marked No. 3) was taken by ARMINOX from a protruding piece of stainless steel reinforcement bar from the bridgehead at pile No. 3 on the east side (see appendix A for details). The location of the sampling point was just above the splash zone. The bridge was built in the years 1937-1941 by the Danish company: Christiani & Nielsen A/S.

Chemical Analysis

In order to identify the steel grade, the sample was analysed by optical spectroscopy (OES).

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Affiliated with the Danish Academy of Technical Sciences

Table 1. Composition (wt%) of the steel sample compared with the AISI 304 specification. The sample was analysed by OES-technique. For complete analysis see appendix B.							
	C	Si	Mn	P	S	Cr	Ni
Sample	0.08	0.53	0.41	0.026	0.027	18.07	8.63
AISI 304 spec.	≤0.08	≤1.00	≤2.00	≤0.045	≤0.030	18.0-20.0	8.0-10.5

From the results in Table 1, it appears that the sample fulfils the specification of the AISI 304-grade. This is one of the most common types of stainless steel in the world, also known as the 18-8-grade. It is noticed that the contents of trace elements in general are well below the acceptable limits. The carbon content is, however, just within the maximum limit of AISI 304.

Microstructure

As a part of the preparation for the chemical analysis, the surfaces of the sample were polished. After this treatment, several cracks through the steel could be seen, see Figure 1 and 2. In order to study the microstructure and these cracks more closely, a microsection of the sample was prepared.

From the characteristic transgranular crack morphology shown in Figure 3, these cracks can be characterized as stress corrosion cracking (SCC).

The microstructure of an undamaged part of the sample is shown in Figure 4. This picture shows a typical and acceptable austenitic structure characterized by relatively coarse grains with twins. From the grain structure, it is assumed that the steel is delivered in a hot-finished and annealed condition. The inclusions orientated along the rolling direction are possibly slag particles.

It should also be noted that the sample was tested to be non-magnetic, which also indicates that the steel has a fully austenitic structure without martensite of ferrite.

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Discussion

The chemical analysis and metallographic examination of the sample shows that the steel quality can be characterized as a so-called 18-8-steel, which is a fully austenitic stainless steel with 18% chromium and 8% nickel. This type of stainless steel was originally developed in Germany around 1910 and used widely from around 1920. At the time when the bridge was built, this type of steel was not a "new" material. The production technology was, of course, not as good as today, but still reasonable. The major critical factor at that time was to achieve sufficiently low contents of undesirable elements, like oxygen, carbon, nitrogen and sulphur. The chemical analysis in Table 1 and the microstructure in Figure 4 shows, however, no signs of extraordinary high contents of these elements in the present sample. The quality of the steel as regards strength is therefore considered to be comparable with a common AISI 304-steel produced in modern steelworks today. The typical mechanical properties of this type of steel in hot-finished and annealed condition are listed in Table 2.

Table 2. Typical mechanical properties of the AISI 304-steel in hot-finished and annealed condition. Source: ASM Speciality Handbook, Stainless Steel Handbook, 1994.

Tensile strength Mpa	0.2% yield strength Mpa	Elongation %	Reduction in area %
515	205	40	50

As regards corrosion resistance, the steel sample was heavily attacked by stress corrosion cracking (SCC). It should, however, be noted that this attack is not related to any weakness of the steel, such as sensitization due to intergranular precipitates. It is believed that the attack is purely a result of the aggressive conditions on the freely exposed surfaces of the steel bars. The critical conditions for stress corrosion cracking of the 18-8-grade may here easily be exceeded, i.e. temperatures above 50°C due to the sunlight, evaporation of chloride containing solutions from the salt mist and high tensile stresses in the steel bar. The same critical conditions cannot be expected for the embedded steel bars, since the temperature and chloride content here will be significantly lower. The reduced access of air as well as the alkalinity and composition of the concrete will also significantly reduce the risk of corrosion of the steel bars within the concrete.

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Based on these considerations, we expect that the stainless steel bars within the concrete are well protected and possibly preserved in the original condition. It is, however, recommended that this be verified by further assessments, e.g. chemical analysis of the pore water in concrete.

Conclusion

Chemical analysis and metallographic examination of the sample shows that the steel quality is comparable with the common AISI 304-grade.

The sample taken from a protruding steel bar was heavily attacked by stress corrosion cracking. The same critical conditions cannot be expected for the embedded steel bars, which presumably are well-preserved.

Yours Sincerely
THE CORROSION DEPARTMENT

Troels Mathiesen

Figure 1. Picture of the sample. The shown side has been used for OES analysis.

Figure 2. Picture of the sample – side 2.

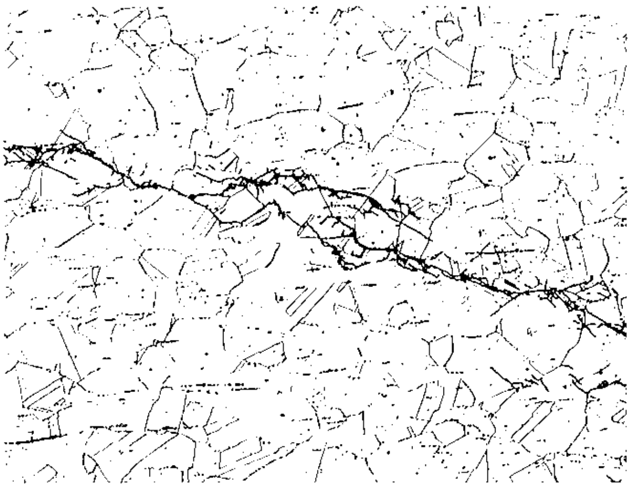

Figure 3. Stress corrosion cracks in the sample. Electrolytically etched in oxalic acid. Magn.: x180.

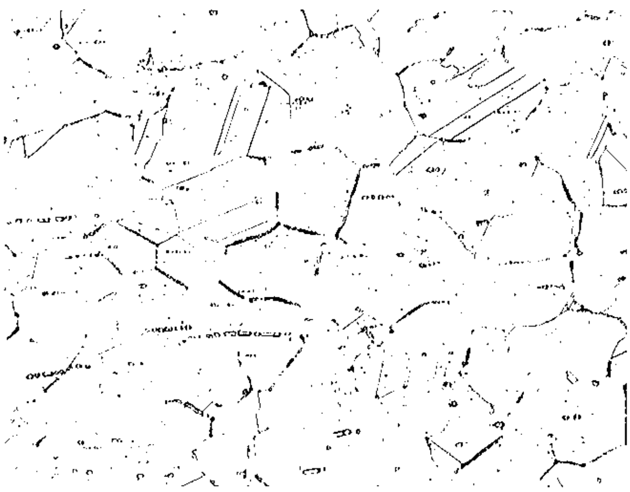

Figure 4. Microstructure of the sample. Electrolytically etched in oxalic acid. Magn.: x370.

Covering letter to reinforcement sample not included.

EXTRACT:

Reinforcement sample from the concrete pier in the Port of Progreso, Yucatan, Mexico.

Reinforcement sample taken from column no. 9 at break-up no. 3.

Sample taken the 14th December 1998 at 15.00 hours.

Analysis by Optical Emission Spectrometry

Appendix B

FORCE INSTITUTE

Division for Materials and Chemical Analysis

Performed using a SPECTROLAB S instrument according to ASTM E 415 and ASTM E 305 with instrument specific modifications.

```
Date/Time : 21.12.98 10:23:03  Mark        :     Program    : FE-31
Status    : 1    Type       : 1  Instrument: L   Weight     :
Sample-No : S 8853    maske ø5mm
Quality   :
Sample-ID : OES8MM
Part      : PROGRESO
```

C %	Si %	Mn %	P %	S %	Cr %
0.080	0.53	0.41	0.026	0.027	18.07
Mo %	Ni %	Al %	Co %	Cu %	Nb %
0.31	8.63	0.001	0.10	0.11	0.007
Ti %	V %	W %	Pb %	Sn %	As %
0.007	0.035	0.014	<0.001	0.014	0.036
Se %	B %	Ta %	Ce %	Fe %	
0.019	0.0016	<0.002	0.004	71.3	

Fe is calculated as difference

Helga Weise

Signature

☐ Due to the size of the sample the analysis has been performed using mask.
Accordingly the results obtained has increased uncertainty compared to analysis under optimal conditions.

☐ Analysis has been performed after remelting of the sample.
Accordingly the results obtained has increased uncertainty compared to analysis of original solid material.

355.E.(A) 07.98

The Intelligent Choice

ARMINOX® stainless steel reinforcement - The maintenance free and the most economical solution for construction all over the world.

ARMINOX® Stainless

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