

# SPECIMEN MONITORING PROJECT

## THE CORROSION RESISTANCE OF LIGHTWEIGHT AGGREGATE CONCRETE

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### 1 INTRODUCTION

This report describes an experiment to compare the corrosion resistance of concrete cast with lightweight aggregate with that of concrete cast using natural aggregate.

Six reinforced concrete slab specimens were cast:

- Two with a lightweight aggregate manufactured from sintered pulverised fuel ash (PFA) (Lightweight Aggregate A);
- Two with lightweight aggregate manufactured from pelletised expanded blast furnace slag (Lightweight Aggregate B); and
- Two with natural aggregate (control specimens).

The specimens containing natural aggregate and Lightweight Aggregate A were cast in August 1998 and ponding started in October 1998. The specimens containing Lightweight Aggregate B were cast in November 1998 and ponding started in January 1999. Ponding was continued until September 2009. Corrosion activity was periodically monitored until January 2006 using standard electrochemical techniques.

In May 2001, one specimen from each pair was broken open and the reinforcing bars inspected to determine the extent and severity of any corrosion. Chloride profiles were determined and it was found that the chloride ion concentration at the level of the reinforcement was similar in the specimens containing natural aggregate and Lightweight Aggregate A but significantly higher in the specimen containing Lightweight Aggregate B. This was consistent with the findings from the electrochemical monitoring and visual inspection of the bars.

In October 2010, chloride profiles were measured in the three remaining specimens which were then broken open and the reinforcing bars inspected to determine the extent and severity of any corrosion.

This report summarises the results of the electrochemical monitoring until January 2006 and describes the results of the chloride profile measurements and destructive examination of the remaining three specimens in October 2010.

## 2 EXPERIMENTAL DETAILS

### 2.1 Details of specimens

The concrete slab specimens had dimensions of 400mm x 350mm x 100mm (Figure 1) and contained four 10mm diameter high yield reinforcing bars and three 16mm diameter stainless steel bars. They were cast with a lip on the cast face to facilitate ponding. The experimental design is given in Table 1. Each pair of specimens was cast from a single batch of concrete using concrete mixes compliant with the Specification for Highway Works Series 1700.

Table 1: Details of specimens

Aggregate type	No. specimens	Water/cement ratio	Specimen numbers
Normal	2	0.45	1A 1B
Lightweight Aggregate A	2	0.50	2A 2B
Lightweight Aggregate B	2	0.50	3A 3B

### 2.2 Ponding and electrochemical monitoring

The specimens were ponded with 500ml of 5% sodium chloride solution. Ponding started after the specimens had fully cured (a minimum of 28 days after casting) and was repeated every fourteen days; this regime resulted in the specimens being wet for 3-4 days and dry for 10-11 days during each cycle.

The outer pairs of bars (T1 and B1, and T4 and B3) were electrically connected together to form a galvanic couple with galvanic currents flowing between the bottom stainless steel bars and the top reinforcing bars (Figure 1). The galvanic currents between each of these pairs of bars were monitored periodically using a zero resistance ammeter (ZRA). The electrode potentials of these pairs of bars and the inner top reinforcing bars (T2 and T3) were also monitored periodically relative to an embedded silver/silver chloride (Ag/AgCl) reference electrode.

Linear polarisation resistance (LPR) measurements were carried out on bars T2 and T3. Two devices were used: the ACM field machine and a portable device. The ACM field machine used a continuous ramp of 20mV whereas the portable device applied a positive 20mV step.

The electrochemical monitoring described above was carried out until January 2006 and the ponding continued until September 2009 (i.e. for nearly 11 years).

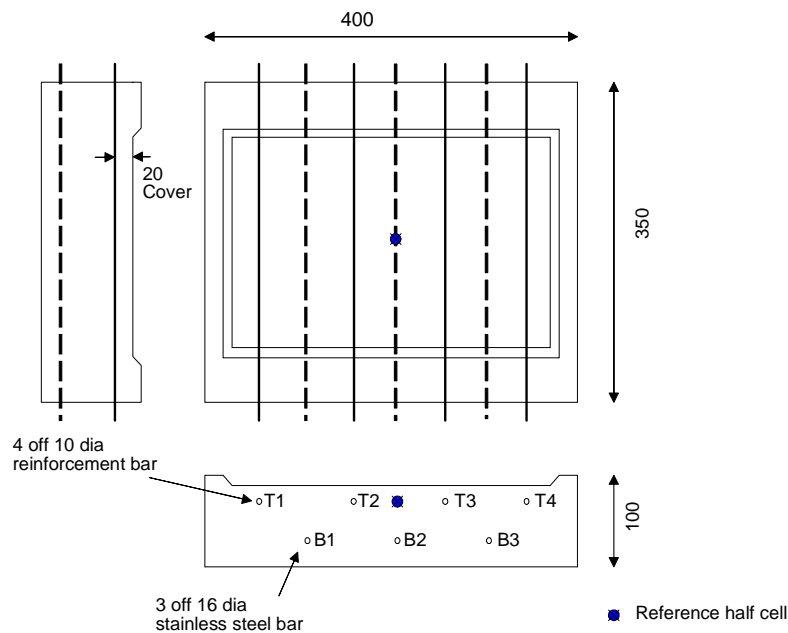


Figure 1: Design of test specimen

### 2.3 Destructive Examination

The ponded area on each of the three remaining specimens was photographed prior to the destructive examination in October 2010, to record any rust staining and cracking on the surface. The photographs were compared with similar photographs taken in December 2004 and January 2006.

Chloride profiles were determined from 50mm diameter cores taken from an area between the top reinforcing bars T1 and T2 along the centre line of each of the three remaining specimens. The cores extended down to the top surface of the bottom stainless steel bar B1 and were approximately 80mm in length. Each core was profile ground in four increments: 0-5mm, 5-15mm, 15-25mm and 25-35mm from the surface. The chloride ion concentration in each increment was measured using automatic potentiometric titration in accordance with the Vinci Construction UK Ltd In House Test Procedure and the results were expressed as the percentage chloride ion by mass of sample.

The specimens were then cut into slices by sawing them transversely approximately 20mm on each side of each of the top (T1-4) high yield bars. It was then relatively easy to remove each of these bars for examination.

The bars from each specimen were photographed to record any corrosion along their length and the total length of corrosion along each bar was measured. The severity of the corrosion was assessed visually and assigned to the following groups:

- 0: no loss in section
- 1: some pitting or loss in section
- 2: significant loss in section such as loss of ribbing
- 3: extensive loss in section extending into the main body of the bar

The results were compared with those from the destructive examination in 2001.

### 3 RESULTS

#### 3.1 Electrochemical monitoring

The criteria for classifying the half-cell potential and LPR corrosion current measurements are given in Table 2.

Table 2: Classification of half-cell potential and LPR corrosion currents

Half-cell potential	
Silver/silver chloride reference electrode	Classification
Potential range (mV)	
> -100	< 10% probability of corrosion
-100 to -250	Probability of corrosion is uncertain
< -250	> 90% probability of corrosion
LPR Corrosion Currents	
Corrosion current ( $\mu\text{A}/\text{cm}^2$ )	Corrosion rate category
< 0.1 to 0.2	Passive
0.2 to 0.5	Low to moderate
0.5 to 1.0	Moderate to high
> 1.0	High

The results from the monitoring of each specimen are shown in Figures 2-4. The top graphs show the variation of galvanic current and half-cell potential (HCP) with time for each pair of outside bars (left and right). The bottom graphs show the variation with time of:

- i) corrosion current (as measured using the ACM field and portable LPR devices); and
- ii) half-cell potentials of the inner bars (T2 and T3).

The half-cell potentials measured on the specimen cast with concrete containing natural aggregate (1B) dropped to about  $-200\text{mV}$  within the first year (Figure 2). After that, the potential of the galvanic couples varied between about  $-200$  and  $-400\text{mV}$  and the potentials of the inner bars have generally remained at about  $-200\text{mV}$ . The potentials of the bars in the specimen cast with Lightweight Aggregate A (2B), generally remained less negative in the range  $0$ - $100\text{mV}$  (Figure 3). For the specimen cast with Lightweight Aggregate B (3B), the potentials dropped to values less than  $-300\text{mV}$  during the first few months of monitoring and then drifted to values less than  $-500\text{mV}$  during the duration of ponding (Figure 4).

The galvanic currents were virtually zero for the bars in the specimens containing natural aggregate and Lightweight Aggregate A, but increased to significant values in the bars from the specimen containing Lightweight Aggregate B.

Figures 2 and 3 show that there was little overall difference in corrosion currents measured using linear polarisation resistance (LPR) for the specimens containing normal aggregate (1B) and Lightweight Aggregate A (2B). Even after nearly seven years of ponding with salt solution, the corrosion currents on bars in the specimens containing Lightweight Aggregate A and natural aggregate were approximately  $0.1\mu\text{A}/\text{cm}^2$  and were therefore in the passive corrosion category. The highest currents were measured on the bars in the specimen containing Lightweight Aggregate B (Figure 4); during the second year of ponding, the mean corrosion currents were in the moderate to high category and during the third and fourth years, the mean increased to the high category ( $>1.0\mu\text{A}/\text{cm}^2$ ) and remained there for the duration of the project.

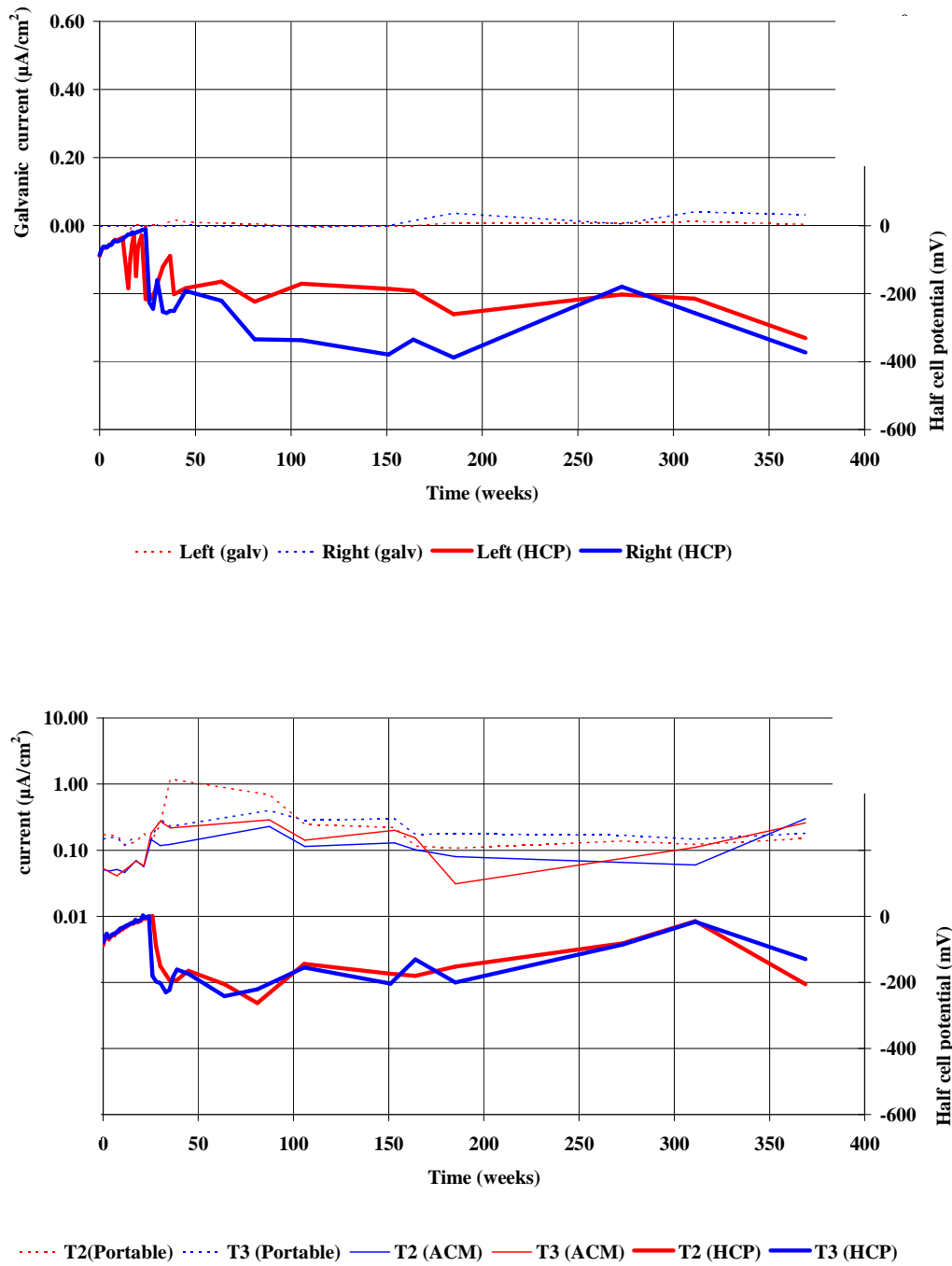


Figure 2: Results from specimen cast from concrete containing natural aggregates (Specimen 1B)

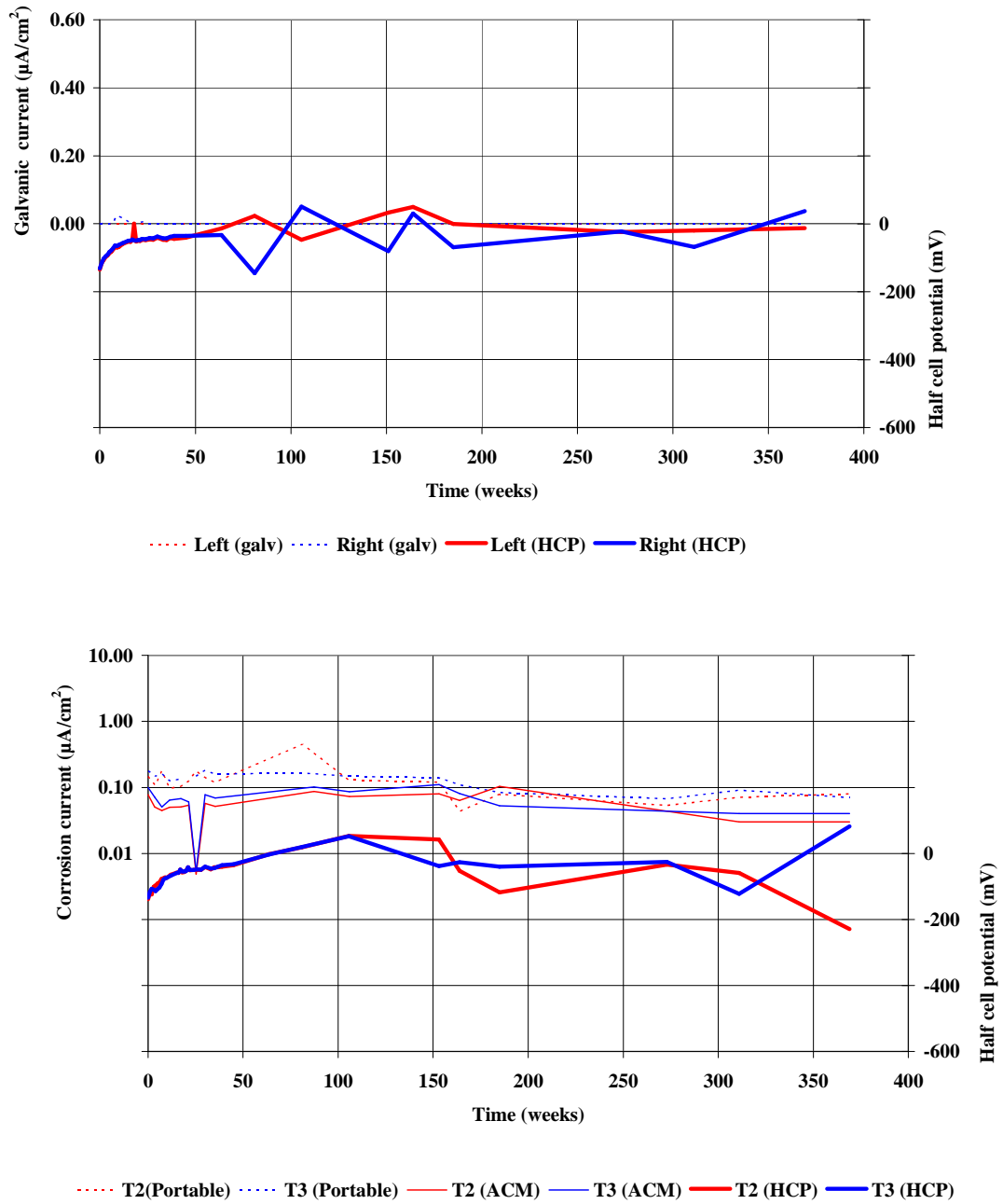


Figure 3: Results from specimen cast from concrete containing Lightweight Aggregate A (Specimen 2B)

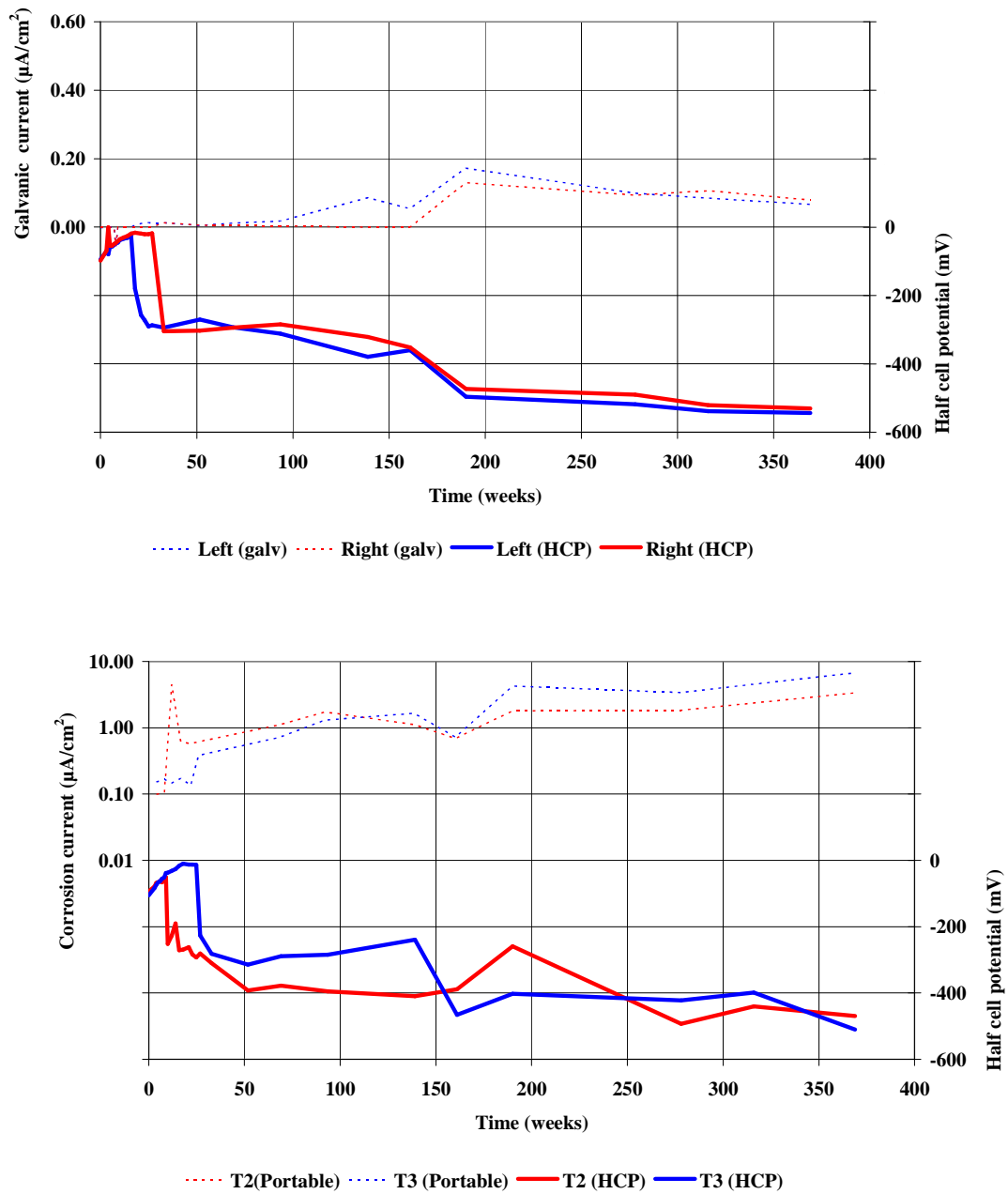


Figure 4: Results from specimen cast from concrete containing Lightweight Aggregate B (Specimen 3B)



### 3.2 Photographs of ponded areas

Figures 5-7 show photographs of the ponded surface of each specimen in December 2004, January 2006 and October 2010. There was no evidence of corrosion on the specimen containing Lightweight Aggregate A (2B). For the Lightweight Aggregate B specimen (3B), for which the electrochemical monitoring indicated moderate to high rates of corrosion, there was an area close to the edge of the specimen over bar T4 where rust staining and slight surface spalling were evident. There was also visible cracking along all the top bars in 2004. This cracking had increased slightly by 2006 but by 2010 the rust staining had been washed away by the ponding. There was also some surface staining above bar T4 on the specimen containing natural aggregate (1B), but there was no visible evidence of cracking. Although the electrochemical monitoring had indicated that the bars in this specimen had generally been in a passive state, the galvanic current flowing in bar T4 had been significantly greater than zero for some of the ponding period and the potential had also been close to -400mV. This would explain the presence of the rust staining on the surface.



December 2004



January 2006



October 2010

Figure 5: Photographs of ponded area of slab 1B  
(cast with natural lightweight aggregate)



December 2004



January 2006



October 2010

Figure 6: Photographs of ponded area of slab 2B  
(cast with Lightweight Aggregate A)



December 2004



January 2006



October 2010

Figure 7: Photographs of ponded areas of slab 3B  
(cast with Lightweight Aggregate B)

### 3.3 Chloride profiles

The chloride profiles measured in 2001 and 2010 (i.e. after about 2 and 10 years of ponding with salt solution), for each specimen are given in Figure 8.

In 2001, the chloride levels in the specimens containing Lightweight Aggregate A and Lightweight Aggregate B were very similar and markedly higher than in the specimen containing natural aggregate. In 2010, the chloride levels in the specimens containing Lightweight Aggregate B remained markedly higher than in the specimen containing natural aggregate. However the values measured in the specimen containing Lightweight Aggregate A were lower than those measured in the other two specimens.

The values measured in 2010 were significantly higher than those measured in 2001 in the specimens cast with natural aggregate and Lightweight Aggregate B whereas they were lower in the specimens containing Lightweight Aggregate A. As this was unexpected, the dust samples taken from specimens containing natural aggregate and Lightweight Aggregate A were retested. The results given in Table 3 show that identical values were obtained from four of the samples and the values from the remaining two samples were within 0.1% of the original measurements. This demonstrates that the original chloride ion concentration data from cores removed in 2010 were valid.

The chloride ion concentrations at the level of the reinforcement (i.e. 20mm from the surface) in 2001 and 2010 are given in Table 4. The chloride ion concentration threshold for the onset of corrosion in concrete is usually taken as 0.3%. The chloride ion concentration in the specimen containing natural aggregate was approximately 9 and 15 times larger than the threshold in 2001 and 2010, respectively. The values for the Lightweight Aggregate B specimens were 18 and 36 times larger than the threshold. These very high levels of chloride explain the amount of reinforcement corrosion found in these specimens. The equivalent values for the specimen containing Lightweight Aggregate A were 10 and 1.7 times the threshold.

The distribution of chlorides measured in 2010 did not reduce with depth from the surface as might be expected, and this deviation from the norm is more pronounced in the specimens containing natural aggregate and Lightweight Aggregate A. A possible explanation is that the specimens would have dried out after ponding stopped in September 2009 and this may have affected the distribution of chlorides within the concrete as moisture moved towards the surface. However, it is not clear why the specimen containing Lightweight Aggregate A appeared to contain less chloride in 2010 than in 2001. It is possible that there was a significant difference between the two samples cast using this aggregate but the reasons for this are unknown.

Table 3: Results of repeat chloride ion concentration measurements

Sample type	Sample depth	Chloride ion concentration (% by weight of cement)	
		Original	Repeat
Normal	2.5	5.8	5.9
	10	5.9	5.9
	20	4.5	4.6
	30	2.4	2.4
Lightweight Aggregate A	2.5	3.8	3.8
	10	2.7	2.7
	20	0.5	0.5
	30	0.1	0.1

Table 4: Chloride ion concentration at the level of the reinforcement

Specimen type	2001	2010
	Chloride ion concentration (by weight of cement) (%)	
Natural aggregate	2.8	4.5
Lightweight Aggregate A	3.1	0.5
Lightweight Aggregate B	5.4	10.8

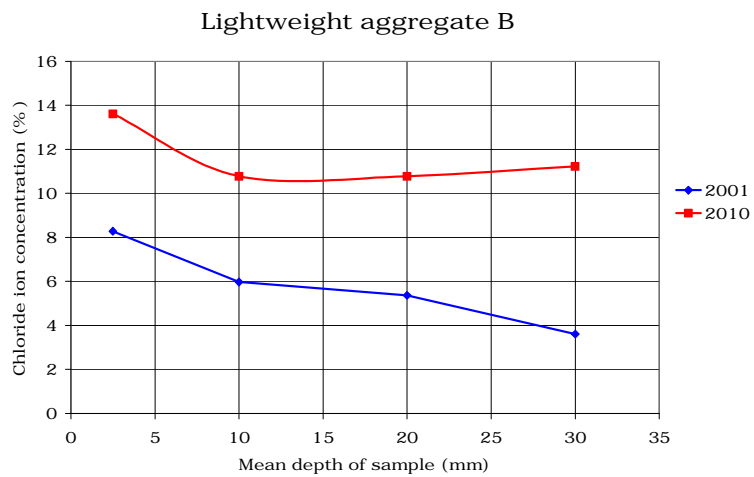
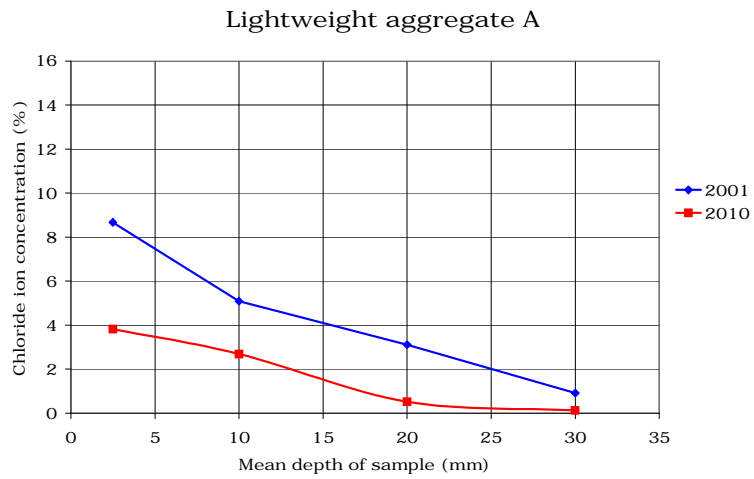
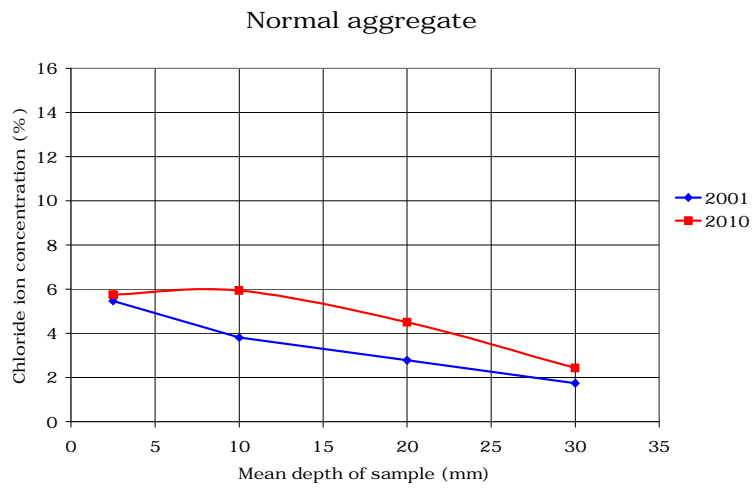


Figure 8: Chloride profiles measured in specimens in 2001 and 2010

### 3.4 Examination of bars removed from specimens

The extent and severity of the corrosion on the bars removed from the specimens in October 2010, compared with those removed in September 2001, are given in Table 5 and Figure 9. The length of corroded bar within each specimen was very variable. For the specimens containing natural aggregate and Lightweight Aggregate B, the average lengths of corroded bar were similar in 2001 and 2010, whereas the average corroded lengths for the bars removed from the specimens containing Lightweight Aggregate A were much greater in 2010.

In 2010, corrosion was more severe on bars taken from specimens containing natural aggregate and Lightweight Aggregate B than on bars taken from the specimens containing Lightweight Aggregate A. In some cases, there was extensive loss of section extending into the main body of the bar, whereas the only significant corrosion on bars taken from the specimen containing Lightweight Aggregate A was pitting and loss of section on one of the bars.

The corrosion on the bars generally occurred in discrete areas along the surface of the bar and was light brown in colour. Figures 10-12 show the top surface of the bars removed in 2001 and the top and bottom surfaces of the bars removed in 2010. There was no corrosion on the underside of any of the bars removed in 2001 nor was there corrosion on the underside of the bars removed from the specimens containing Lightweight Aggregate A in 2010, whereas there was significant corrosion on the underside of the bars removed from the specimens containing natural aggregate and Lightweight Aggregate B in 2010.

Figures 13-15 show close up views of the areas of corrosion on the bars removed from the specimens in 2010. It is clear that the corrosion was much more severe on the bars from the specimens containing natural aggregate and Lightweight Aggregate B than on the bars removed the specimen containing Lightweight Aggregate A.



Table 5: Length and severity of corrosion of bars removed from specimens in 2001 and 2010

Bar Number	Length of bar affected (mm)		Severity of corrosion	
	2001	2010	2001	2010
Natural aggregate				
1	190	220	1	3
2	100	50	0	2
3	80	110	1	3
4	120	90	1	3
Mean	123	117		
Lightweight Aggregate A				
1	20	110	0	0
2	55	50	0	1
3	30	60	0	0
4	20	230	0	0
Mean	31	112		
Lightweight Aggregate B				
1	195	250	2	2
2	180	110	1	3
3	190	90	2	3
4	80	60	3	3
Mean	161	152		

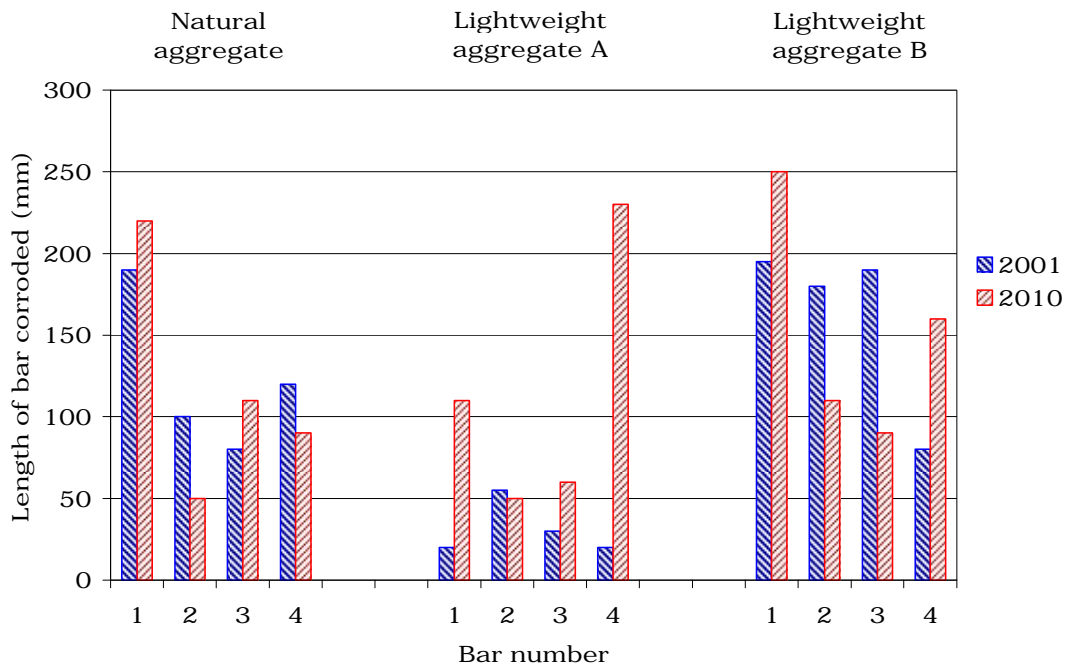
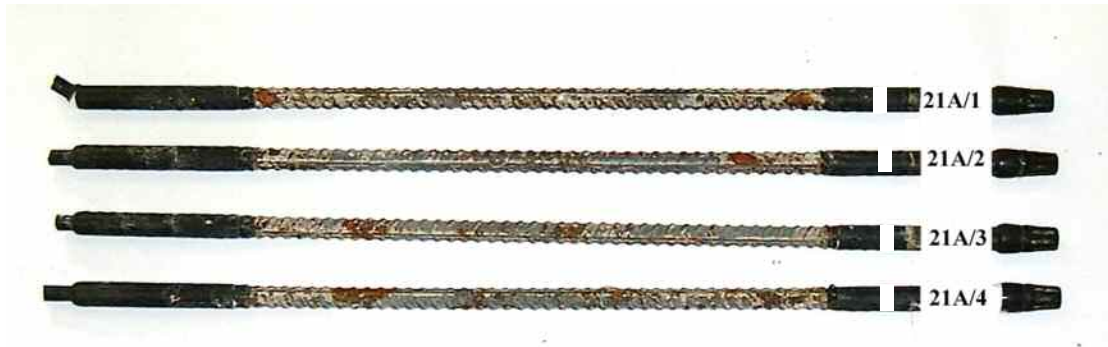


Figure 9: Length of corrosion on bars removed from specimens

Specimen 1A (2001) (top surface)



Specimen 1B (2010) (top surface)

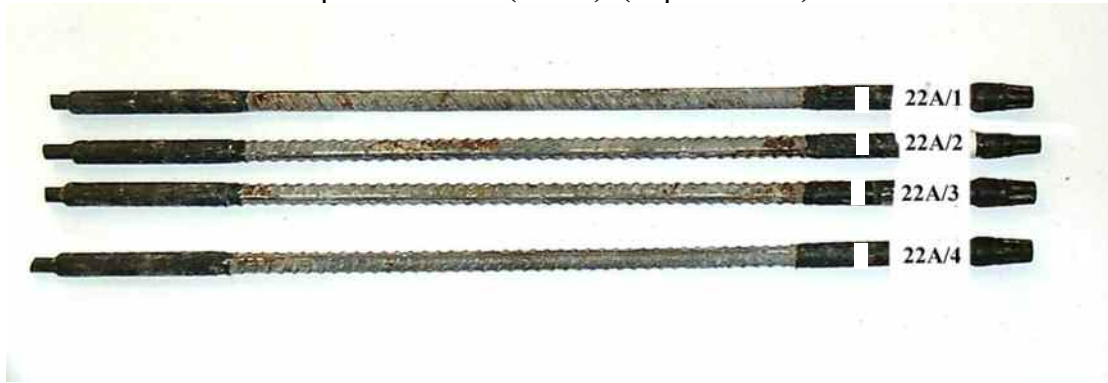


Specimen 1B (2010) (bottom surface)



Figure 10: Photographs of bars removed from natural aggregate specimens

Specimen 2A (2001) (top surface)



Specimen 2B (2010) (top surface)



Specimen 2B (2010) (bottom surface)



Figure 11: Photographs of bars from removed Lightweight Aggregate A specimens

Specimen 3A (2001) (top surface)



Specimen 3B (2010) (top surface)



Specimen 3B (2010) (bottom surface)



Figure 12: Photographs of bars removed from Lightweight Aggregate B specimens



Figure 13: Close up photograph of bars removed from natural aggregate specimens



Figure 14: Close up photograph of bars removed from the specimens containing Lightweight Aggregate A



Figure 15: Close up photograph of bars removed from the specimens containing Lightweight Aggregate B

#### 4 DISCUSSION OF RESULTS AND CONCLUSIONS

The results of the corrosion monitoring until January 2006 showed that there was more corrosion activity in the specimen containing Lightweight Aggregate B than in the specimens containing natural aggregate and Lightweight Aggregate A. This was consistent with photographs of the ponded surfaces taken in 2006 which showed that there was more cracking and corrosion on the surface of the specimen containing Lightweight Aggregate B.

Ponding continued for nearly four years after the last set of corrosion measurements were made in 2006. During this time, significant amounts of salt were absorbed into the specimens and the chloride ion concentrations at the level of the reinforcement were well in excess of the chloride threshold for corrosion in all specimens in both 2001 and 2010, with the exception of the specimen containing Lightweight Aggregate A in 2010 where it was only 1.7 times the threshold. The highest chloride ion concentrations measured in 2010 were in the specimen containing Lightweight Aggregate B; the concentration at the level of the reinforcement was about twice that in the specimen containing natural aggregate.

The low chloride ion concentrations measured in 2010 in the specimen containing Lightweight Aggregate A compared with the measurements made in 2001 may have been as a result of differences between the two specimens cast using Lightweight Aggregate A.

The condition of the bars removed from the specimens broken up in 2010 was consistent with the results of the electro-chemical monitoring and the measurements of chloride ion concentrations. Corrosion was significantly more severe on the bars removed from the specimens containing Lightweight Aggregate B and natural aggregate than on those removed from specimen containing Lightweight Aggregate A. There was some pitting on one of the bars from the Lightweight Aggregate A specimen, whereas there was extensive loss of section extending into the main body of the bar on three of the bars from the natural aggregate and Lightweight Aggregate B specimens and some loss of section and ribbing on a fourth bar from each these specimens.

The results of these experiments demonstrated that the use of lightweight aggregate in concrete can be as effective as normal weight aggregate in resisting the ingress of chlorides and protecting the reinforcement against corrosion.