

SPECIMEN MONITORING PROJECT

THE USE OF RECYCLED CONCRETE AGGREGATE IN STRUCTURAL CONCRETE

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1 INTRODUCTION

In 2005, TRL completed a research project for the Highways Agency to investigate the use of recycled concrete aggregate (RCA) in structural concrete. The objectives of the project were:

- (i) to update clauses 1702 and 1703 of the Specification for Highway Works (SHW) to permit the use of RCA.
- (ii) to draft an Advice Note on the use of RCA.

As part of the project, experiments were carried out to determine the engineering properties and durability of structural concretes in which proportions (up to 100%) of the natural coarse aggregates were replaced with RCA. Durability was assessed by accelerated laboratory testing and casting some larger specimens for long term natural exposure. The results from the experimental work were reported by Calder and Roberts (2005). Some specimens were retained for further investigation as part of a monitoring project for the Highways Agency.

The larger specimens were installed at an exposure site adjacent to the A66 in County Durham in September 2005 to enable their resistance to chloride ingress and freeze thaw to be evaluated over the long-term. Corrosion monitoring and visual inspection of the specimens were undertaken periodically.

This report describes the results of the electrochemical monitoring of the laboratory specimens, measurements of chloride ingress into the specimens and an assessment of the condition of the reinforcing bars removed from the specimens.

2 EXPERIMENTAL PROGRAMME

For the original research completed in 2005, concrete specimens were cast from a total of 28 mixes with different combinations of blended cements, natural aggregates and proportions of RCA (Table 1). Two blended cements were used: CEM1 combined with ground granulated blast furnace slag (GGBS) and pulverised fuel ash (PFA). Two types of natural aggregates, uncrushed gravel and crushed limestone, were used and specimens were cast with twenty, sixty and a hundred percent of the natural aggregate replaced with Type II RCA from Derby, Reading and Frome. Calder and Roberts (2005) reported that the RCA from Reading contained significant quantities of brick and asphalt, whereas the RCA from Derby and Frome were virtually free from these impurities. The mixes were specified as C50 ordinary structural concrete conforming to Clause 1701 of the Specification for Highway Works. The water/cement ratio had to be reduced and the water content increased as the proportion of RCA was increased to maintain the required strength and workability.

Table 1: Numbering of mixes

Mix	RCA	Proportion of RCA (%)		Mix	RCA	Proportion of RCA (%)
CEM1/GGBS				CEM1/PFA		
Natural aggregate: gravel						
1	-	0		15	-	0
2	Derby	20		16	Frome	20
3		60		17		60
4		100		18		100
5	Reading	20		19	Reading	20
6		60		20		60
7		100		21		100
Natural aggregate: limestone						
8	-	0		22	-	0
9	Derby	20		23	Frome	20
10		60		24		60
11		100		25		100
12	Reading	20		26	Reading	20
13		60		27		60
14		100		28		100

3 CHLORIDE INGRESS

3.1 Experimental details

Chloride ingress was measured by ponding slab specimens fortnightly with a 5% salt solution. Two specimens were cast from each mix design. They contained four high tensile reinforcing bars and three stainless steel bars (Figure 1). The outer pairs of bars in each specimen (T1 and B1, and T4 and B3) were electrically connected together so that galvanic currents flowing between the bottom stainless steel bars and the top reinforcing bars could be monitored using a zero resistance ammeter (ZRA). The half-cell potentials between the pairs of bars and an embedded silver/silver chloride (Ag/AgCl) reference electrode were also monitored. The half-cell potential and linear polarisation resistance (LPR) corrosion currents in the top reinforcing bars (T2 and T3) were also monitored. The criteria for classifying the half-cell potential and LPR corrosion current measurements are given in Table 2. For the purpose of this experiment, it was assumed that corrosion may be occurring when the galvanic current is $>0.1\mu\text{A}$. This value was an arbitrary choice based on the monitoring graphs rather than any widely accepted criteria.

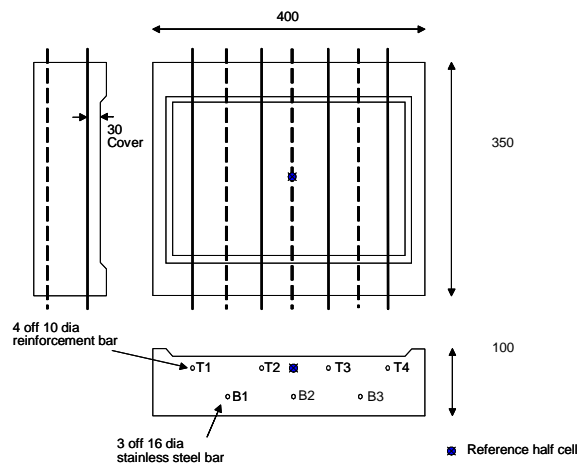


Figure 1: Specimen details for resistance to chloride ingress

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

Half-cell potential		
Reference electrode		Classification
Copper/copper sulphate	Silver/silver chloride	
Potential range (mV)		
> -200	> -100	< 10% probability of corrosion
-200 to -350	-100 to -250	Probability of corrosion is uncertain
< -350	< -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 first set of corrosion measurements was made on the CEM1/GGBS specimens four weeks prior to the start of ponding and a further set just before ponding started. The first set of corrosion measurements on the CEM1/PFA specimens was made about two weeks after the start of ponding.

Corrosion is initiated once sufficient chlorides reach the reinforcement and it was planned to continue ponding and monitoring for about 12 months after the onset of corrosion so that significant loss of section of the steel could occur. One of the pair of specimens cast from each mix design would then be broken up; chloride profiles determined and the bars removed for examination. The remaining specimen from each pair would be retained for further ponding and monitoring.

Ponding the specimens continued to the September 2009. Half-cell potentials and corrosion currents were measured periodically until July 2007, regularly at the start of the project but less frequently once the readings had stabilised.

Chloride profiles were determined by taking a single 50mm diameter core from an area between the top reinforcing bars T1 and T2 along the centre line of a specimen. The cores extended to the top surface of the bottom stainless steel bar S1 and were approximately 80mm in length. Each core was profile ground in four increments: 0-5mm, 5-15mm, 15-25mm and 25-35mm. Automatic potentiometric titration was used to analyse the samples from each increment in accordance with the Taylor Woodrow In House Test Procedure. The results were expressed as the percentage chloride ion by mass of sample. Cores were taken from one of the specimens cast using each mix in August 2008 and March 2009 for the CEM1/GGBS and CEM1/PFA mixes, respectively (i.e. after the specimens had been ponded for about 5¼ years).

The chloride contents were expressed as the percentage chloride ion by mass of cement plus the total mass of the cement replacements. This was in accordance with footnote b in Table 10, Clause 5.2.7 of BS EN 206-1 (2000) which requires that when Type II additions (for example GGBS and PFA) are used they should be taken into account for the determination of the cement content. The mix details given in Appendix D of TRL Published Project Report PPR036 (Calder and Roberts, 2005) were used to calculate the total cement content in each mix design so that the chloride ion concentration could be expressed as a percentage of the total cement content.

3.2 Results of electrochemical monitoring

Typical results from the electrochemical monitoring are shown in Figures 2 and 3 (Mix 2). For the duration of the experiment, the potentials of both the inner and outer bars remained more positive than -100mV. The measured galvanic currents in the outer bars remained close to zero and the LPR currents in the two inner bars remained less than $0.1\mu\text{A}/\text{cm}^2$. These results indicate that both the inner and outer bars in these specimens remained in a passive state.

By contrast, Figure 4 shows results for the outer bars from specimens cast from Mix 12. The measured galvanic currents on one of the outer bars (12A/L) increased to $1.46\mu\text{A}$ after 127 weeks reducing to $0.20\mu\text{A}$ after 218 weeks. This was associated with a similar decrease in potential to values more negative than -100mV. The behaviour of bars 12A/R and 12B/L were similar, but less marked. These results indicate that significant galvanic currents, which would lead to corrosion, were flowing through the outer bars for at least part of the time. For the specimens cast using Mix 6 (Figure 5), the LPR corrosion currents in the inner bars were initially approximately $0.20\mu\text{A}/\text{cm}^2$, reducing to $0.10\mu\text{A}/\text{cm}^2$ after 127 weeks and then increasing slightly when the potentials dropped to values less than -100mV. This indicated that corrosion may have started to develop in the inner bars.

Mix 2

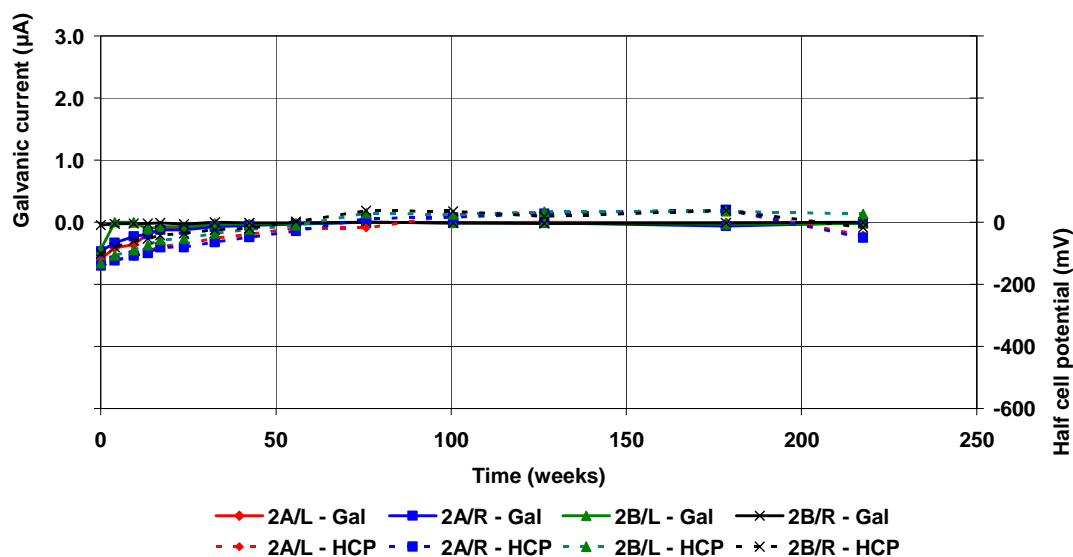


Figure 2: Typical results from corrosion monitoring of outer bars¹

Mix 2

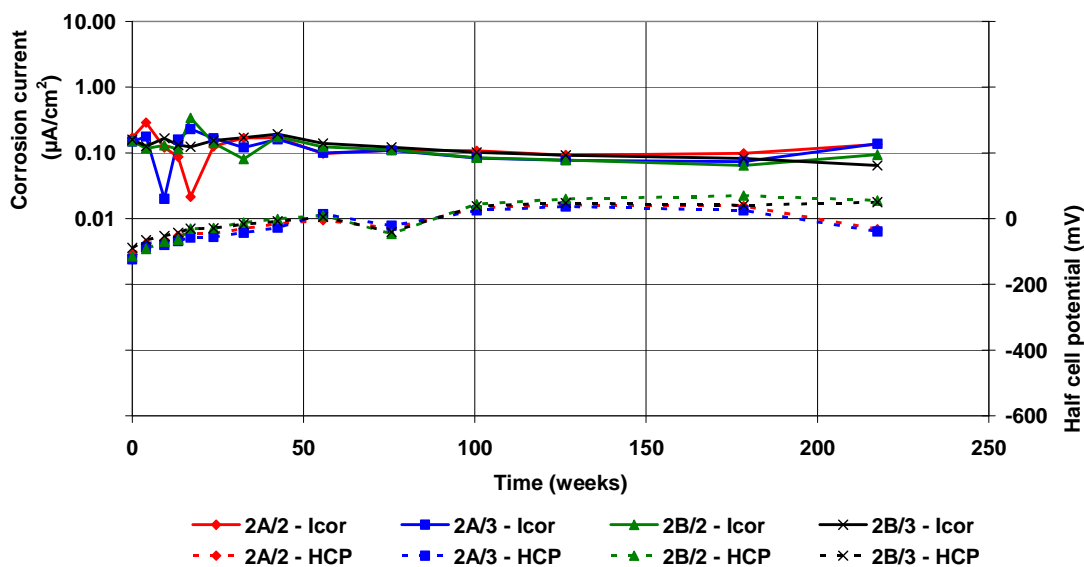


Figure 3: Typical results from corrosion monitoring of inner bars²

¹ Notation: 2A/L is the current between bars B1 and T1 in Specimen A cast from mix 2 and 2A/R is the current between bars B3 and T4. Similarly for 2B/L and 2B/R.

² Notation: 2A/2, 2A/3, 2B/2 and 2B/3 refer to bars T2 and T3 in Specimens A and B for mix 2.

Mix 12

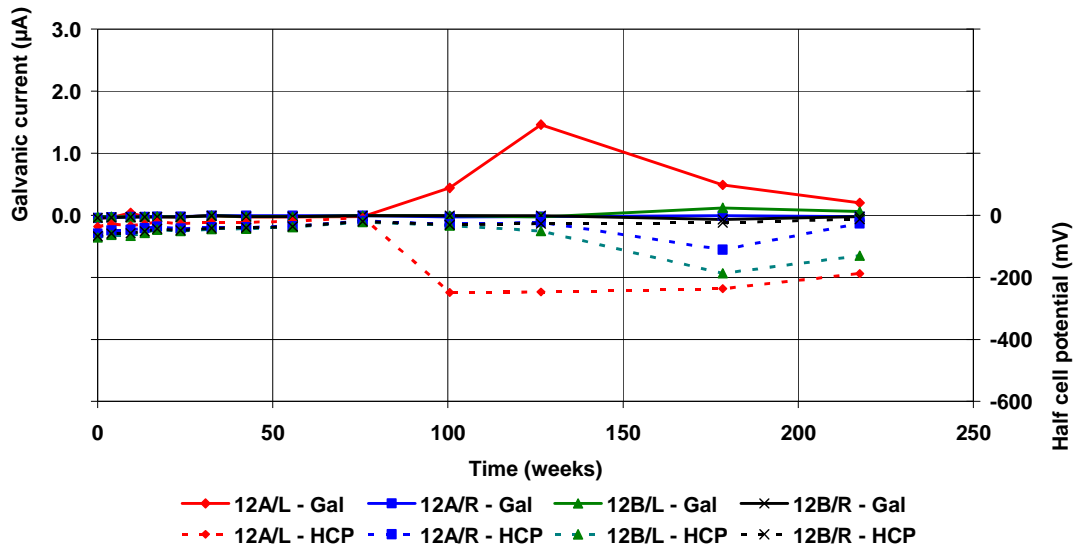


Figure 4: Results of galvanic current and half-cell potential measurements on specimens cast using mix design 12

Mix 6

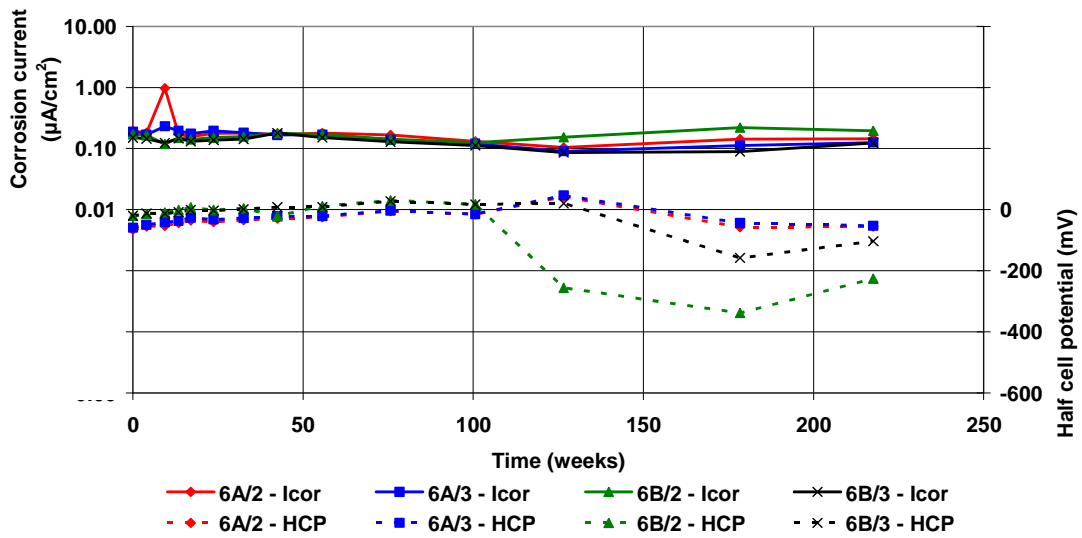


Figure 5: Results of galvanic current and half-cell potential measurements on specimens cast using mix design 6

For most of the specimens, the half-cell potential measurements indicated that the probability of corrosion was $<10\%$ ($>-100\text{mV}$) and LPR measurements were in the passive range (<0.1 to $0.2\mu\text{A}/\text{cm}^2$). However, the half-cell potentials and LPR corrosion currents measured on bars in a few specimens were within the uncertain probability of corrosion and low to moderate corrosion rate category, for at least part of the time.

Similar results were found from the measurements of galvanic current. For some bars they were greater than $0.1\mu\text{A}$ which indicated some corrosion activity but for the majority, they were less than $0.05\mu\text{A}$, indicating no corrosion activity.

To assess the extent corrosion activity in the bars during the course of the ponding and to compare the results from specimens cast using different mixes, the number of times that each of the measurements indicated that there was some corrosion activity was plotted on a histogram. The criteria used to define corrosion activity were:

- Galvanic currents $> 0.1\mu\text{A}$ (significantly greater than zero)
- Half-cell potentials $< -100\text{mV}$ (probability of corrosion is uncertain)
- LPR corrosion current $>0.2\mu\text{A}/\text{cm}^2$ (low to moderate rate)

The electrochemical monitoring was undertaken 14 times on the CEM1/GGBS specimens and 9 times on the CEM1/PFA specimens.

The results from the galvanic current and half-cell potential measurements on the outer bars for the CEM1/GGBS specimens are shown in Figures 6 and 7. They indicate that the corrosion activity was very limited, with only a very few bars showing galvanic currents significantly greater than zero. For the inner bars (Figures 8 and 9), the LPR corrosion rate measurements indicated more corrosion activity, although there were fewer instances where half-cell potentials were less than -100mV . Despite LPR corrosion currents $>0.2\mu\text{A}/\text{cm}^2$ measured on some bars on a significant number of occasions, the rates were in the low to moderate range and therefore the amount of corrosion damage to the bars was likely to be very limited. Figures 10-13 indicate that there was even less corrosion activity in the specimens containing CEM1/PFA.

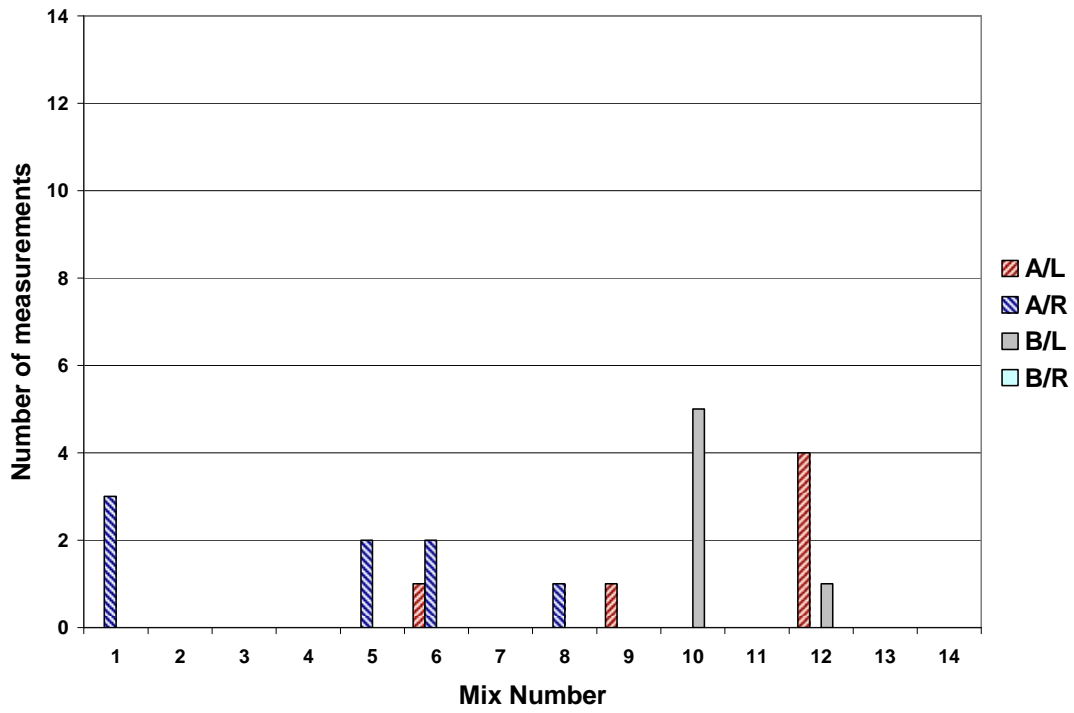


Figure 6: Number of galvanic current measurements on each outer bar greater than 0.1 μA (CEM1/GGBS mixes)

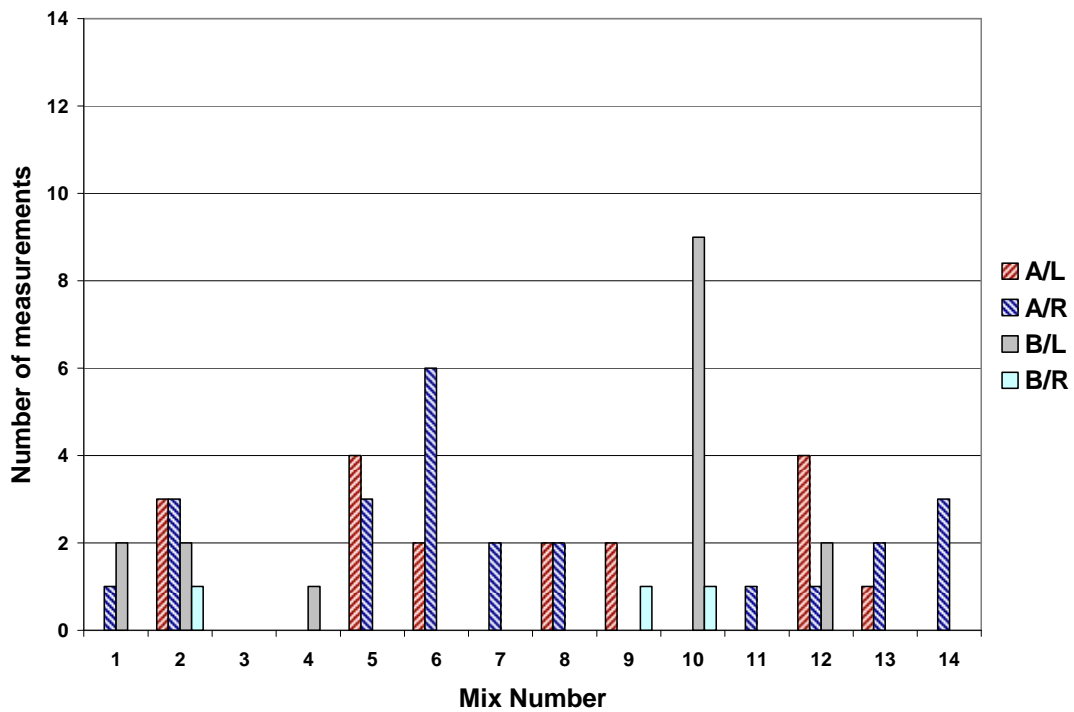


Figure 7: Number of half-cell potential measurements on each outer bar more negative than -100mV (CEM1/GGBS mixes)

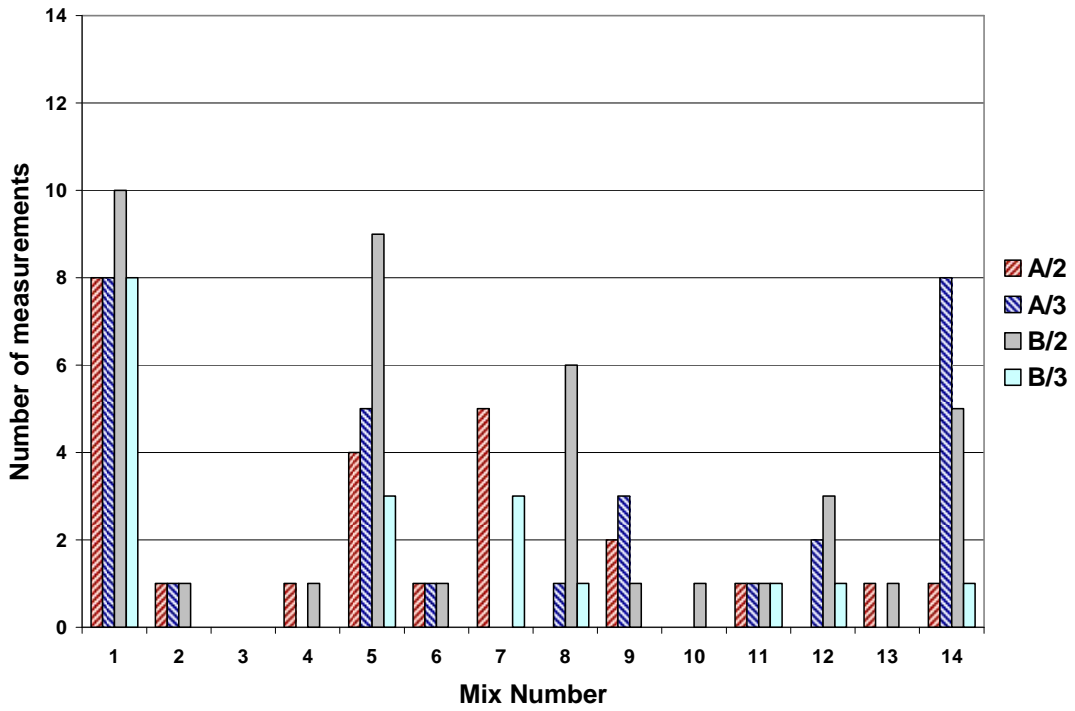


Figure 8: Number of LPR measurements on each inner bar greater than $0.2\mu\text{A}/\text{cm}^2$ (CEM1/GGBS mixes)

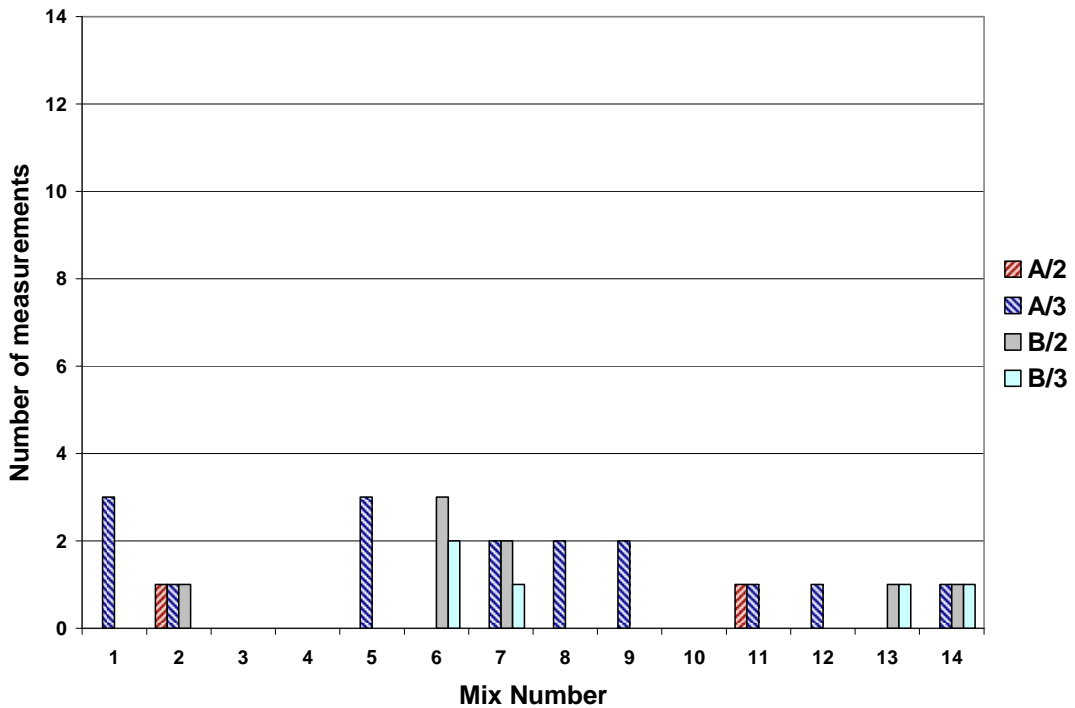


Figure 9: Number of half-cell potential measurements on each inner bar more negative than -100mV (CEM1/GGBS mixes)

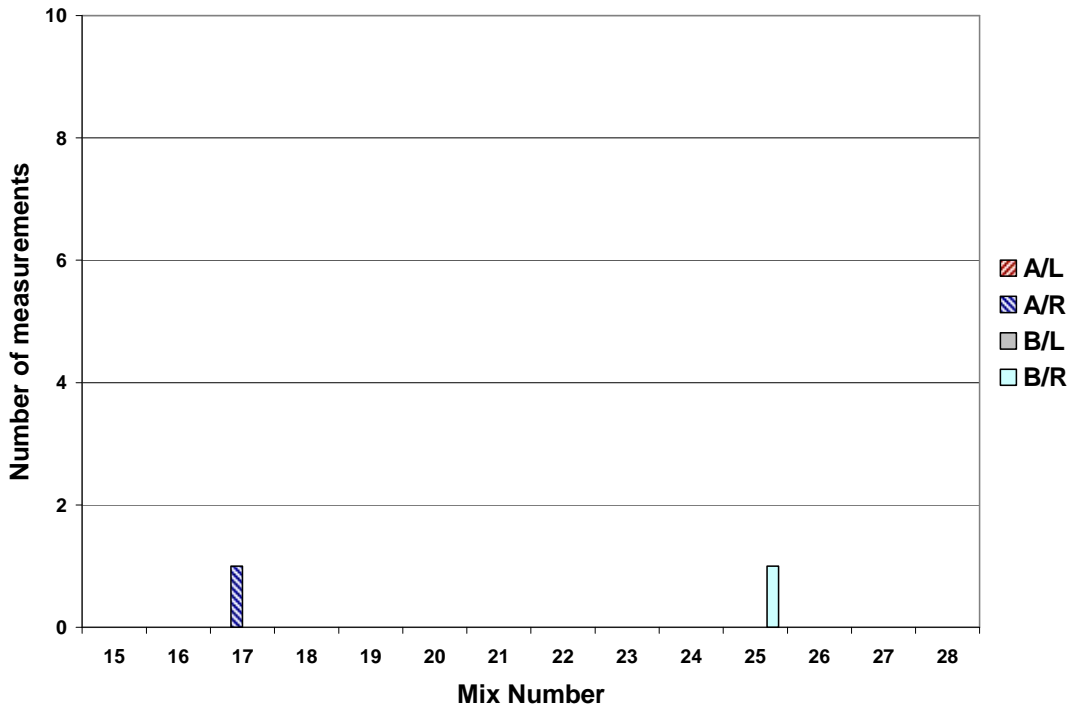


Figure 10: Number of galvanic current measurements on each outer bar greater than 0.2µA (CEM1/PFA mixes)

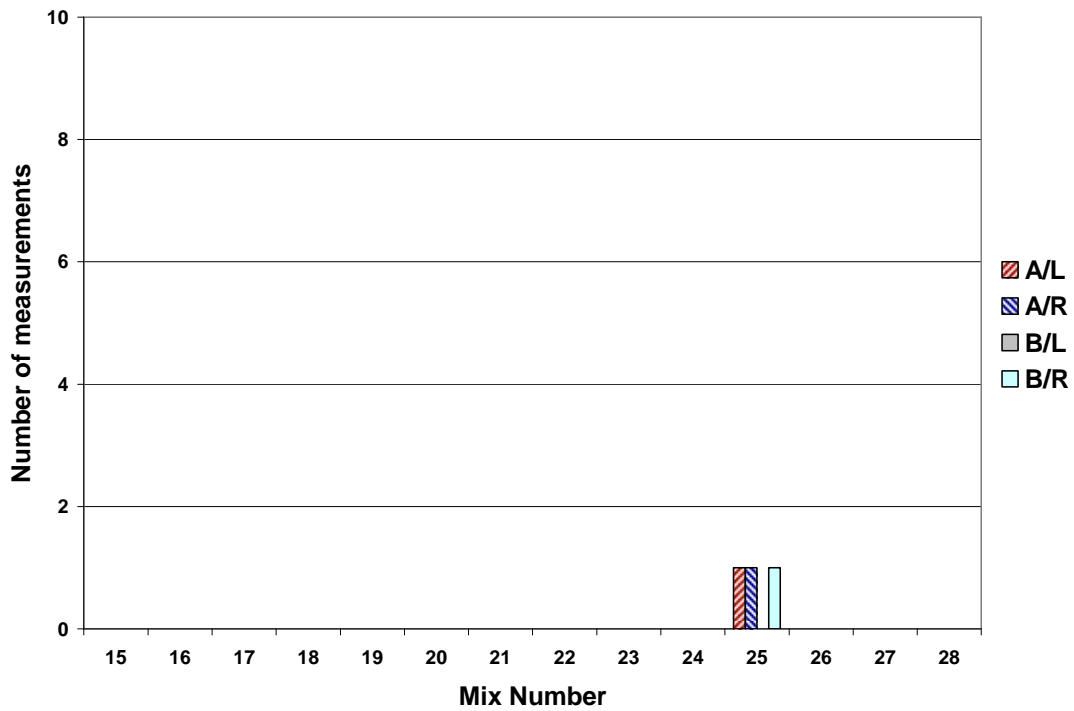


Figure 11: Number of half-cell potential measurements on each outer bar more negative than -100mV (CEM1/PFA mixes)

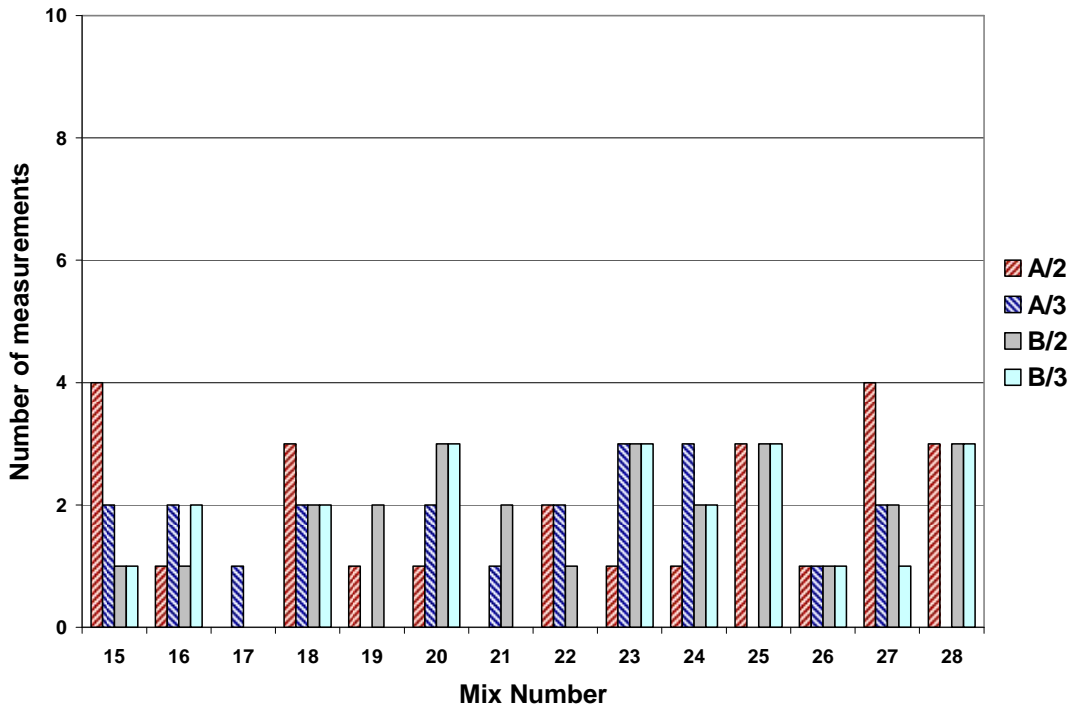


Figure 12: Number of LPR measurements on each inner bar greater than $0.10\mu\text{A}/\text{cm}^2$ (CEM1/PFA mixes)

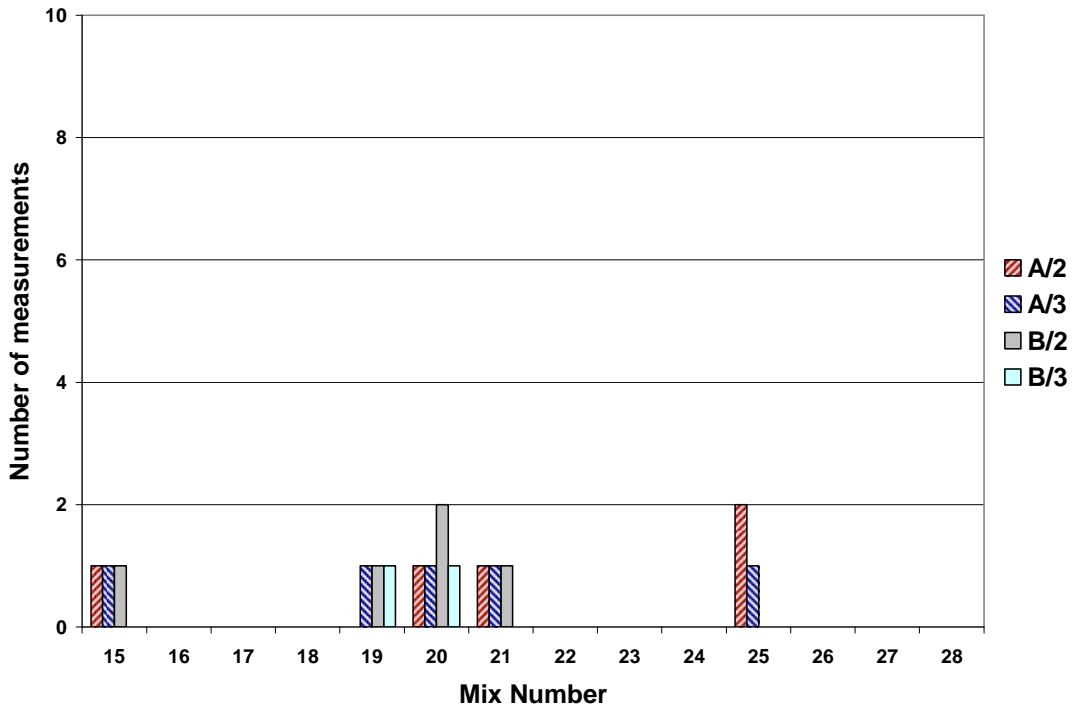


Figure 13: Number of half-cell potential measurements on each inner bar more negative than -100mV (CEM1/PFA mixes)

3.3 Chloride profiles

Plots of chloride ion concentration as a percentage of the total cement content against mean sample depth are shown in Figures 14-21. Each figure gives the data for a particular combination of natural aggregate and RCA with 0%, 20%, 60% and 100% of the natural aggregate replaced. In most cases, the chloride levels were highest at the surface reducing to relatively low values at the level of the reinforcement (30mm from the surface). For three of the specimens containing CEM1/GGBS and two of those containing CEM1/PFA, the highest chloride ion concentration was 10mm from the surface.

The chloride ion concentrations in specimens containing CEM1/GGBS were higher than in those containing CEM1/PFA, with the exception of the specimen containing 20% RCA from Reading.

The chloride ion concentration at the level of the reinforcement and the cement content of each mix are given in Tables 3 and 4.

For the specimens containing CEM1/GGBS and RCA, the chloride ion concentrations at the level of the reinforcement were lower than in the control specimens in all cases with the exception of the specimens containing limestone and 20% and 60% RCA from Derby.

For CEM1/PFA specimens containing gravel and RCA, the chloride ion concentrations at the level of the reinforcement were similar to those in the control specimens with the exception of the specimen containing 20% RCA from Reading where the chloride ion concentration was significantly higher than in the control specimen.

For the CEM1/PFA specimens containing limestone and RCA, the chloride ion concentrations at the level of the reinforcement were higher than in the control specimen.

The chloride ion concentration at the depth of the reinforcement exceeded the threshold of 0.3% by weight cement for the onset of corrosion in five of the specimens containing CEM1/GGBS and in one of the specimens containing CEM1/PFA. The chloride ion concentrations in the samples cast from the remaining mixes were below the threshold which was in agreement with the electrochemical monitoring which detected very limited corrosion activity.

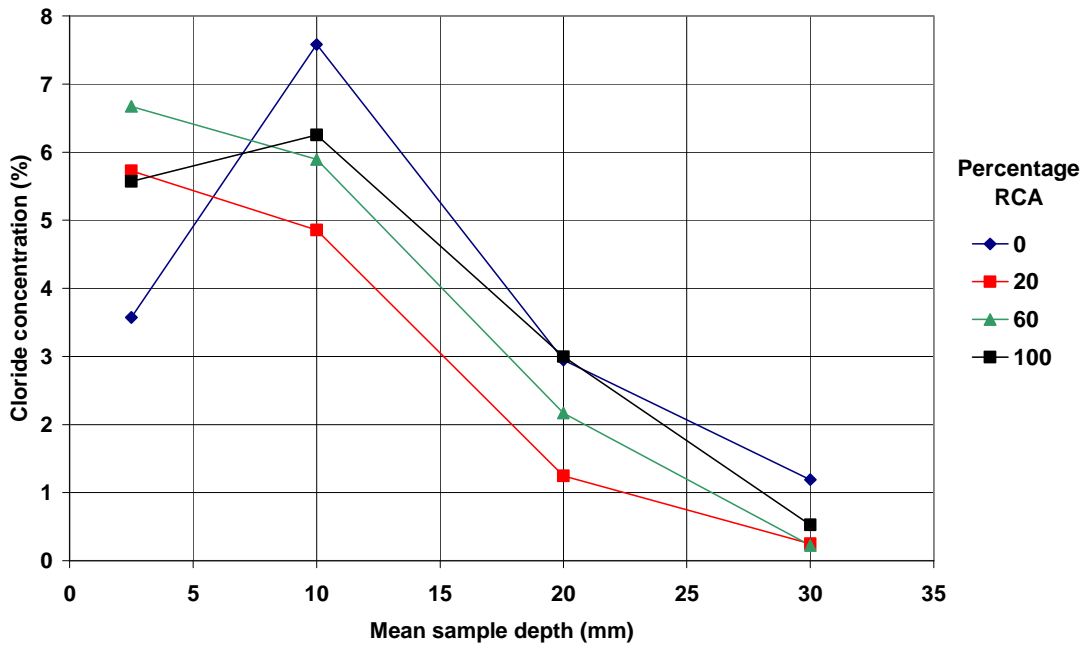


Figure 14: Chloride profiles for specimens cast using CEM1/GGBS with gravel and recycled concrete aggregate from Derby

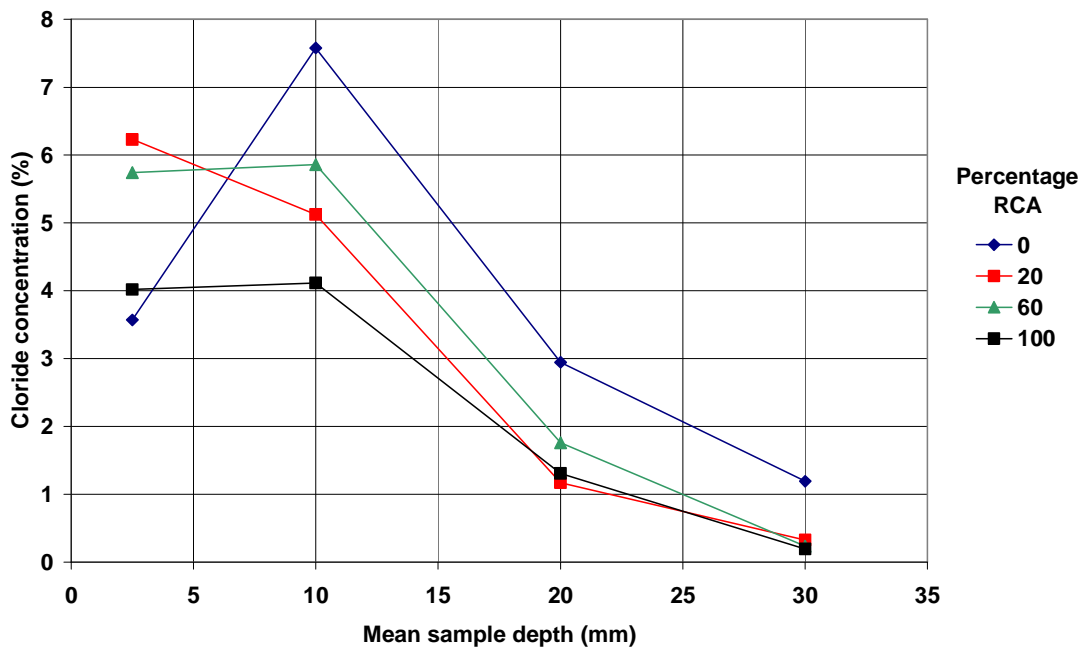


Figure 15: Chloride profiles for specimens cast using CEM1/GGBS with gravel and recycled concrete aggregate from Reading

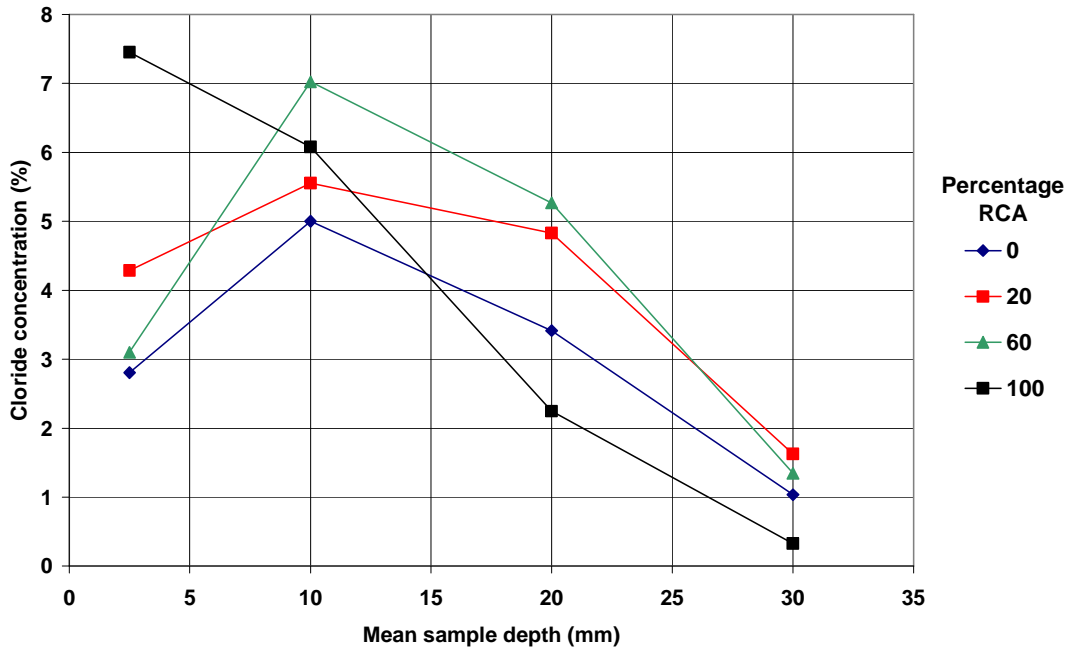


Figure 16: Chloride profiles for specimens cast using CEM1/GGBS with limestone and recycled concrete aggregate from Derby

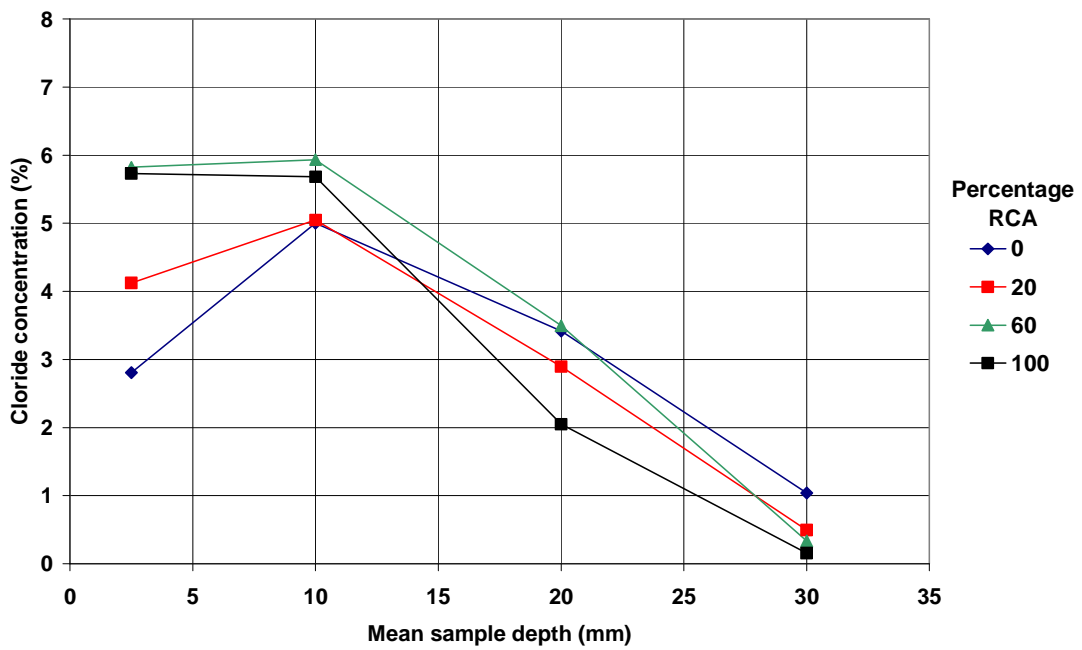


Figure 17: Chloride profiles for specimens cast using CEM1/GGBS with limestone and recycled concrete aggregate from Reading

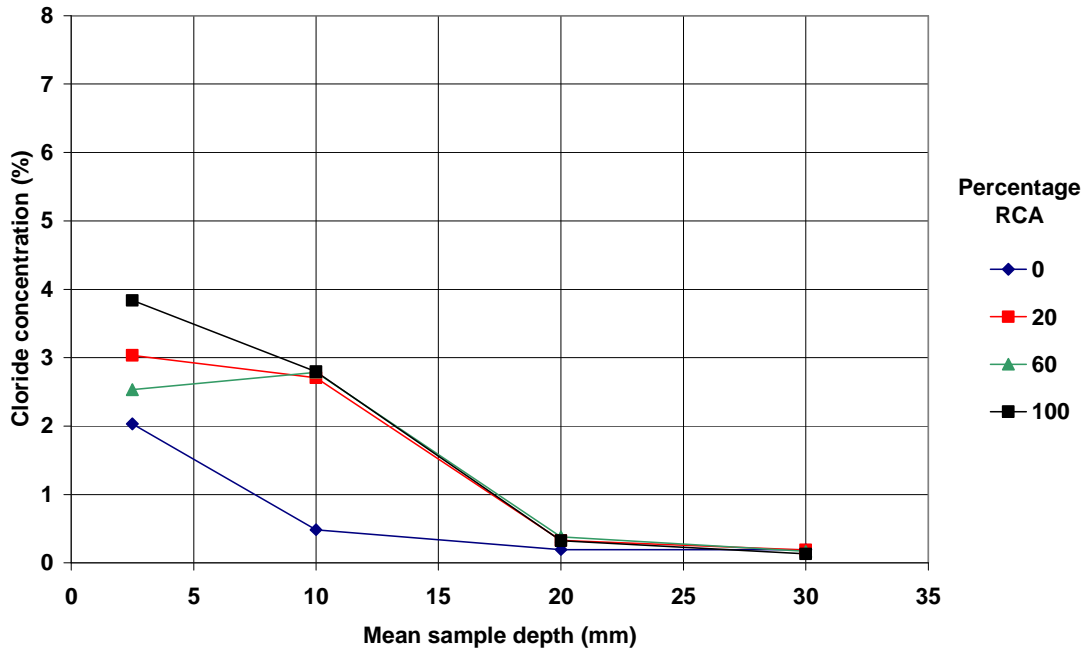


Figure 18: Chloride profiles for specimens cast using CEM1/PFA with gravel and recycled concrete aggregate from Frome

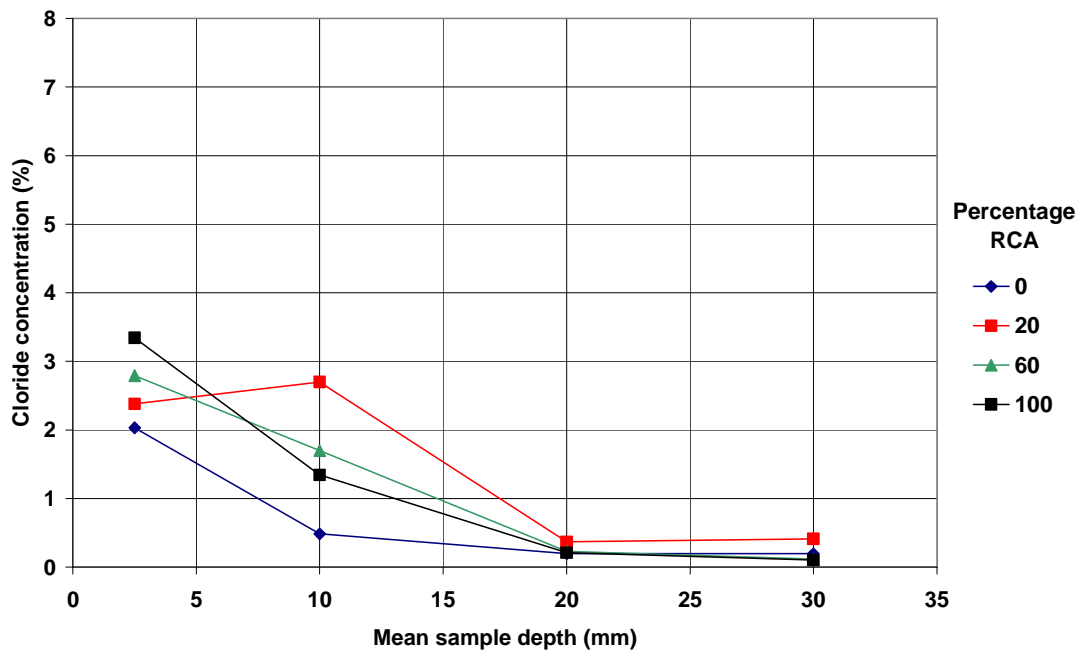


Figure 19: Chloride profiles for specimens cast using CEM1/PFA with gravel and recycled concrete aggregate from Reading

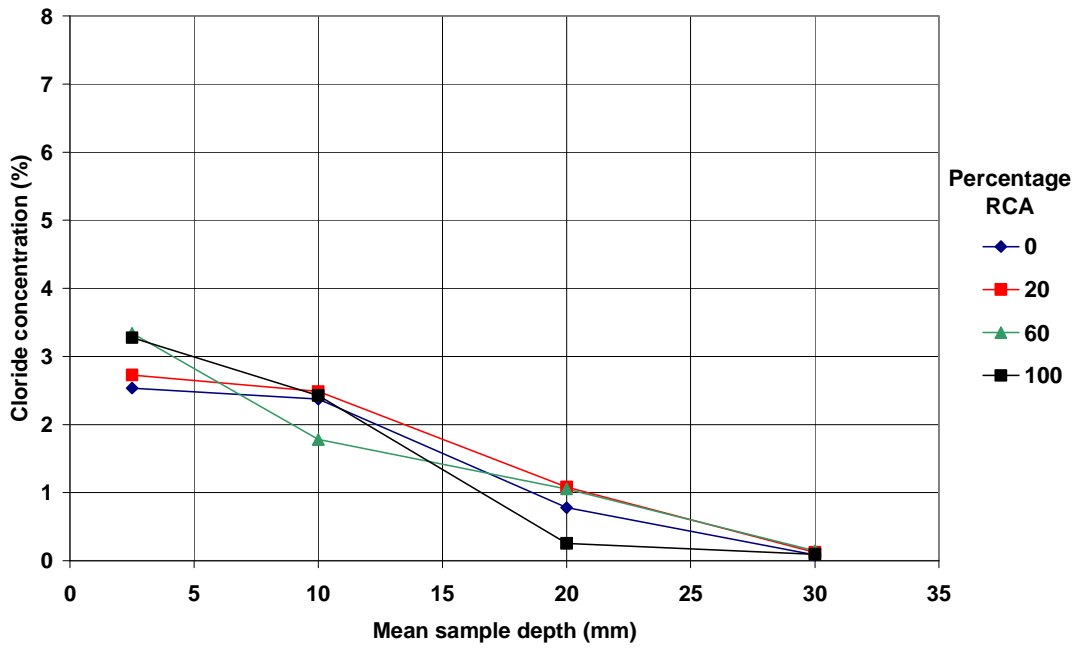


Figure 20: Chloride profiles for specimens cast using CEM1/PFA with limestone and recycled concrete aggregate from Frome

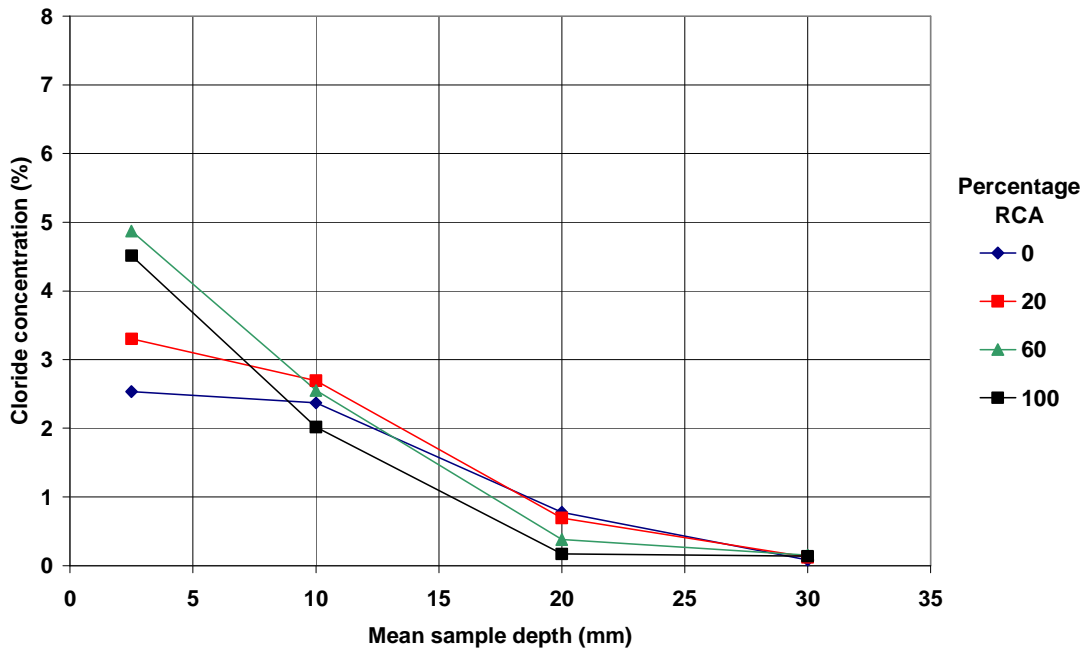


Figure 21: Chloride profiles for specimens cast using CEM1/PFA with limestone and recycled concrete aggregate from Reading

Table 3: Cement content and chloride ion concentration at the level of the reinforcement for concrete containing CEM1/GGBS

Mix	Natural aggregate	RCA	Prop RCA	Cement content (%)	Chloride ion concentration (%)	
					By weight of sample	By weight of cement
1	Gravel	Control	0	16.0	0.19	1.19
2		Derby	20	16.1	0.04	0.25
3			60	18.0	0.04	0.22
4			100	19.0	0.10	0.53
5		Reading	20	15.4	0.05	0.32
6			60	17.1	0.04	0.23
7			100	20.7	0.04	0.19
8	Limestone	Control	0	16.4	0.17	1.04
9		Derby	20	16.6	0.27	1.63
10			60	17.1	0.23	1.35
11			100	18.3	0.06	0.33
12		Reading	20	16.3	0.08	0.49
13			60	18.0	0.06	0.33
14			100	19.5	0.03	0.15

Table 4: Cement content and chloride ion concentration at the level of the reinforcement for concrete containing CEM1/PFA

Mix	Natural aggregate	RCA	Prop RCA	Cement content (%)	Chloride ion concentration (%)	
					By weight of sample	By weight of cement
15	Gravel	Control	0	20.7	0.04	0.19
16		Frome	20	21.4	0.04	0.19
17			60	23.7	0.04	0.17
18			100	30.8	0.04	0.13
19		Reading	20	21.9	0.09	0.41
20			60	26.5	0.03	0.11
21			100	29.0	0.03	0.10
22	Limestone	Control	0	24.5	0.02	0.08
23		Frome	20	25.0	0.03	0.12
24			60	27.5	0.04	0.15
25			100	31.8	0.03	0.09
26		Reading	20	24.5	0.03	0.12
27			60	26.3	0.04	0.15
28			100	29.3	0.04	0.14

3.4 Destructive examination of selected specimens

In 2010, ten specimens were broken open and the reinforcing bars removed and examined. The specimens selected for destructive examination were those with the same mix designs as the specimens cast for the long-term exposure trials (Section 1). Details of the mixes are given in Table 5. One specimen was selected from each of the ten pairs of specimens that had been cast.

Table 5: Mix designs used for the exposure tests

Mix	Natural aggregate	RCA	Proportion of RCA (%)
CEM1/GGBS			
1	Gravel	-	0
6		Reading	60
8	Limestone	-	0
13		Reading	60
CEM1/PFA			
15	Gravel	-	0
17		Frome	60
20		Reading	60
22	Limestone	-	0
24		Frome	60
27		Reading	60

To remove the reinforcing bars, the specimens were cut transversely approximately 20mm from both sides of each of the top (T1-4) reinforcing bars. It was then relatively easy to remove each of these bars for examination.

The top and bottom surface of each set of four bars from each specimen were photographed. Figures 22-31 show the photographs of the top bars. All the bars were lightly corroded in discrete areas. The corrosion was brown and only on the surface without any loss of section on either the main bar or the ribs. The corrosion was mainly on the top surface of the bar nearest the ponded area, but was also evident on the bottom surface of some of the bars. As it was not practical to assess the length of corrosion on each of the bars, the extent and severity of corrosion on each set of four bars were subjectively assessed by visual examination and ranked. This was undertaken independently by two observers.

The extent and severity of corrosion was assessed by laying out each set of four bars on a laboratory bench in numeric order using the number of the mix design (i.e. 1, 6, 8 etc). Each observer inspected the bars and arranged the sets in order of their perception of the extent and severity of corrosion. The set of bars with the least corrosion was assigned the value one and the set with the most corrosion was assigned a value of ten. The results obtained by the two observers are given in Table 6. It should be noted that this type of assessment is very subjective and it would not be expected that there would be an exact match between the results from the two observers. In this case however there was good, but not exact, agreement. The results were combined by taking the average ranking for each mix design.

Table 6: Corrosion ranking of bars removed from specimens

Corrosion ranking	Observer	
	A	B
	Mix design	
1	20	27
2	27	24
3	24	20
4	15	17
5	17	15
6	13	1
7	1	8
8	8	13
9	22	22
10	6	6

Note: 1 = least corrosion, 10 = most corrosion



Figure 22: Top surface of bars removed from Specimen 1A



Figure 23: Top surface of bars removed from Specimen 6A



Figure 24: Top surface of bars removed from Specimen 8A



Figure 25: Top surface of bars removed from Specimen 13A



Figure 26: Top surface of bars removed from Specimen 15A



Figure 27: Top surface of bars removed from Specimen 17A



Figure 28: Top surface of bars removed from Specimen 20A



Figure 29: Top surface of bars removed from Specimen 22A



Figure 30: Top surface of bars removed from Specimen 24A



Figure 31: Top surface of bars removed from Specimen 27A

3.5 Discussion of results of chloride ingress experiments

The results of the corrosion monitoring and measurements of chloride ion concentration for the specimens broken open in 2010 are summarised in Table 7. The specimens are listed in the order of their corrosion ranking.

In all but the two specimens cast using CEM1/GGBS with 100% gravel and limestone (mix designs 1 and 8), the chloride ion concentration at the level of the reinforcement was close to or less than the 0.3% threshold for corrosion. Although there is insufficient data to draw firm conclusions, there was also a trend for more corrosion on the bars from specimens cast with 100% natural aggregates than on bars from specimens cast with 60% RCA. (Three of the four mixes cast from the natural aggregate were ranked between 6 and 10). This suggests that the use of 60% replacement of natural aggregate with RCA may improve the resistance to chloride ingress.

There was some light corrosion on all the sets of the bars, with exception of those removed from the specimens cast using mix 22. There was less corrosion on bars from specimens containing CEM1/PFA than on bars from those containing CEM1/GGBS. This confirms the results of the electrochemical monitoring which showed that there was less corrosion activity in the CEM1/PFA specimens than the CEM1/GGBS specimens.

These observations are based comparatively small levels of corrosion and chloride ion concentrations at the level of the reinforcement.

Table 7: Summary of results of chloride ingress experiments

Corrosion ranking ¹	Mix design	Cement blend/natural aggregate	RCA/ proportion (%)	Galvanic current ²	LPR ³	HCP ⁴	Chloride ion concentration ⁵ (%)
1	27	PFA/ Limestone	Reading/ 60	0	6	0	0.15
2	20	PFA/ gravel	Reading/ 60	0	3	2	0.11
3	24	PFA/ Limestone	Frome/ 60	0	4	0	0.15
4=	15	PFA/ gravel	None	0	6	2	0.19
4=	17	PFA/ gravel	Frome/ 60	1	1	0	0.17
6	1	GGBS/ gravel	None	1	16	6	1.19
7	13	GGBS/ limestone	Reading/ 60	0	1	3	0.33
8	8	GGBS/ limestone	None	1	1	6	1.04
9	22	PFA/ Limestone	None	0	4	0	0.08
10	6	GGBS/ gravel	Reading /60	3	2	8	0.23

Notes:

- 1 1 = least corrosion, 10 = most corrosion (see Section 3.4, Table 6)
- 2 Number of galvanic current measurements $> 0.1\mu\text{A}$ (significantly greater than zero)
- 3 Number of LPR corrosion current measurements $> 0.2\mu\text{A}/\text{cm}^2$
- 4 Number of half-cell potential measurements $< -100\text{mV}$ (probability of corrosion uncertain)
- 5 Chloride ion concentration at level of reinforcement (per cent by weight of cement)

4. CONCLUSIONS

- After 5¼ years of fortnightly ponding with a 5% salt solution, the ingress of chloride ions has not been sufficient to initiate to significant corrosion. In the majority of cases, the chloride ion concentration at the level of the reinforcement was below the 0.3% by weight of cement threshold for the onset of corrosion.
- For the majority of the specimens there was less chloride ingress into the specimens containing RCA, either as a partial or total replacement for natural aggregate, than into the control specimens cast from 100% natural aggregate.
- In general there was less chloride ingress into specimens containing PFA than into those containing GGBS. The average chloride ion concentration (by weight of sample) at the level of the reinforcement in specimens containing PFA was 36% of that in specimens containing GGBS.
- The chloride ion concentration at the depth of the reinforcement exceeded the threshold of 0.3% by weight cement chloride for the onset of corrosion in five of the specimens containing CEM1/GGBS and in one of the specimens containing

CEM1/PFA. The chloride ion concentrations in the samples cast from the remaining mixes were below the threshold.

- Corrosion in the specimens containing CEM1/PFA was less than in those containing CEM1/GGBS which is consistent with the lower ingress of chlorides.
- There was very little corrosion on any of the bars removed from the specimens, but the bars from specimens cast with 100% natural aggregates were slightly more corroded than those from specimens cast with 60% replacement with RCA.

5. REFERENCES

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